A study of vowel nasalization using instantaneous spectra

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Abstract

Nasalization of vowels is a phenomenon where oral and nasal tracts participate simultaneously for the production of speech. Acoustic coupling of oral and nasal tracts results in a complex production system, which is subjected to a continuous changes owing to glottal activity. Identification of the duration of nasalization in vowels, and the extent of coupling of oral and nasal tracts, is a challenging task. The present research focuses on the changes in instantaneous vocal tract system response to study the effects of co-articulatory load of nasals on vowels. The dominant resonance frequency (DRF) contour derived from the spectra illustrates the contribution of oral and nasal resonances during nasalization. The extent of coupling determines the dominance of these resonances during glottal open and closed phases. A higher extent leads to more decay of energy for the oral resonances, and hence the vowel spectra exhibits a dominant nasal resonance. A comparison of the proposed parameters is made with the previously suggested measures. Several examples of segments of vowels in the context of nasal consonants for English language for both male and female speakers of English are used to illustrate different aspects of the proposed analysis method.

Key words: nasalized vowels; oral—nasal coupling; zero time windowing; HNGD spectra; dominant resonance frequency

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1. Introduction

Nasalization of vowels occurs when the air flow takes place through both oral and nasal tracts during production of vowels. Oral vowels are produced by exciting an open oral tract with pseudo-periodic vibration of the vocal folds at the glottis. Nasal consonants are produced with lowering the velum and closing the oral tract, resulting in airflow only through the nasal tract. Coupling of an open oral and nasal tracts results in presence of a nasal signature in the vowel spectrum. Extent of this coupling dictates the volume of airflow through each of these tracts. The nasal tract consists of multiple sinus cavities, and acts as a branched cavity to the open oral tract during nasalization. This overall system is further subjected to glottal activity, resulting in a complex production system changing continuously with time. A dynamic and involuntary nature of glottal and velar movement makes the identification of presence of nasalization in vowels a challenging task. Understanding the phenomena of vowel nasalization in speech is important for the improvement of several speech applications, such as automatic speech recognition, speech pathology, language identification, and interactive voice response systems.

Study of the phenomenon of vowel nasalization has been motivated to highlight the contrast between oral and nasal vowels. Previous studies explored the spectro-temporal characteristics of vowel segments derived across a variety of acoustic and linguistic contexts. Early developments towards the task have highlighted the presence of a low frequency spectral peak (within 250–300 Hz range) in vowel spectra, as a characteristic signature of coupling of nasal and oral tracts [1, 2, 3, 4]. These studies also emphasized on the role of spectral zero in 700–1800 Hz range, and widening of the first formant (F1) bandwidth, as supportive evidences of nasalization in vowels. Presence of a pole–zero pair around first formant (F1) of the vowel, and a spectral peak around 1 kHz, is also noted for several cases of nasalized vowel segments [5]. The effect of introduction of a synthetic pole–zero pair in low frequency range, and increasing the amplitude of the first harmonic, is studied for its contribution towards perception of nasality in vowels [1, 6]. Further studies have discussed the importance of spectral peak in 250-450 Hz range as an important cue to determine the presence of nasalization in vowel spectra [7, 8, 9, 10].

These studies have propelled the task of automatic identification of nasalization in speech, based on parameters derived from vowel spectra. Spectral

correlates A1-P1 and A1-P0 have been proposed to highlight the contrast within oral and nasalized vowels [11, 12]. A1 is defined as amplitude of the harmonic peak closest to an estimated location of F1. P1 is amplitude of the nasal peak in vicinity of F1, whereas P0 is amplitude of first resonance peak at low frequencies. A large shape of the nasal tract contributes towards broadening of F1, consequently lowering its amplitude in nasalized vowels. An average value of both these correlates were found to be lower for nasalized vowels than for oral vowel segments. The study presents a comparison between nasalized vowels for anticipatory (occurring after) and carryover (occurring before) nasal contexts, for these correlates. An 'orality threshold' measure is proposed based on the extent of lowering of velum, to distinguish nasalized vowels from oral vowels [5]. However, a high degree of variability in the nasalization phenomena across utterances, speakers and languages mitigates weakens the reliability on such a measure [13]. A set of nine acoustic features have been proposed to detect the presence of nasalization in vowel segments [14]. These features capture the low frequency spectral behavior of nasalized vowels, such as change in energy and bandwidth of F1, and other spectral peaks, and changes in energy profile of different bands in low frequency range. All these parameters are derived on the short-time spectral representation of vowel spectrum obtained using short time Fourier transform (STFT). Dominant peaks in group delay (GD) spectrum have been utilized to detect hypernasality in pathological speech [15]. The GD spectrum is derived as derivative of the phase component of STFT with respect to frequency. Advantages of the GD spectrum is that it provides sharper spectral peaks compared to the STFT based spectrum [16].

Importance of the low frequency resonance occurring below or in the range of F1, for identification of nasalization in vowels, has consistently been highlighted by several studies. The present study utilizes this knowledge to derive correlates from the instantaneous spectra to address the identification of presence of nasalization, along with its duration and extent, in vowel segments. The spectral representation obtained from the zero time windowing (ZTW) method gives a good resolution in temporal and spectral domains [17]. The method, therefore, proves helpful to study the dynamic characteristics of the production system during coupling of the oral and nasal tracts, subjected to the glottal activity. The paper explores the effects of contextual load of nasals on vowels, for different CV/VC pairs in the English language. The paper is organized as follows: Section 2 presents the zero time windowing method, and the motivation to the study. Section 3 discusses the analysis

of oral and nasalized vowels using dominant resonance frequencies (DRFs) derived from the instantaneous spectra. Section 4 illustrates the behavior of DRF contour for different extent of coupling of oral and nasal tracts. Section 5 discusses the observations based on proposed hypothesis for the behavior of DRF contour for oral and nasalized vowel segments for several CV/VC pairs. Section 6 presents a summary to the paper.

2. Background and motivation

This section discusses the zero time windowing method to obtain the spectral characteristics at good temporal resolution. Distinction in the dominant spectral behavior of oral vowels and nasal consonants provide the necessary motivation to explore vowel nasalization phenomena using ZTW.

2.1. Zero time windowing method

The zero time windowing (ZTW) method utilizes a heavily decaying window, giving more weightage to samples near the point of application of the window, called the zero time [17]. This windowing is motivated by the zero frequency filter (ZFF) which is a sharp resonator centered around 0 Hz [18]. The time domain analog of this operation is a heavily decaying window function given by,

$$w_1[n] = \begin{cases} 0, & n = 0, \\ 1/4sin^2(\pi n/2N), & n = 1, 2, \dots, N-1, \end{cases}$$
 (1)

where N is the length of the window in samples corresponding to a duration of l ms. The windowed signal is given as x[n] = s[n]w[n], where s[n] is the speech signal, and the window function is given as $w[n] = w_1^2[n]w_2[n]$. $w_2[n]$ is another window which helps to reduce the ripple effect due to truncation, and is given by

$$w_2[n] = 4\cos^2(\pi n/2N), \quad n = 0, 1, \dots, N - 1,$$
 (2)

Application of the window function $w_1[n]$ can be interpreted as an integration operation performed twice in the frequency domain [17]. Spectral characteristics of the windowed segment x[n] are thus obtained by successive differentiation. The spectrum is represented using the Hilbert envelope of

the differenced numerator group delay (HNGD) function. The numerator of GD (NGD) function is given by,

$$\tau(\omega) = X_R(\omega)Y_R(\omega) + X_I(\omega)Y_I(\omega). \tag{3}$$

where $X(\omega)=X_R(\omega)+jX_I(\omega)$ is the discrete—time Fourier transform (DTFT) of x[n], and $Y(\omega)=Y_R(\omega)+jY_I(\omega)$ is the DTFT of nx[n]. The Hilbert envelope of the twice differenced NGD (HNGD) shows the formant peaks with a good resolution [19]. A window with duration $l \leq$ average pitch period gives the changes in the acoustic system response within a glottal cycle [20]. The window w[n] is shifted by one sample, to obtain the spectrum at every sampling instant.

Figure 1 illustrates the contrast in spectral estimates obtained using HNGD and STFT methods. Figure 1(b) shows the HNGD spectrogram for a segment of vowel /e/ uttered by a male speaker given in Fig. 1(a). The HNGD spectrogram is obtained across an analysis segment duration l=4 ms, shifted at every sample. Changes in the system response appear in an instantaneous manner in the HNGD spectrum. Figure 1(c) shows the STFT spectrogram of the segment. The STFT is computed at every sampling instant using l=4 ms Hann window. The averaging effect on the spectral details can be seen in the STFT spectrogram. Movement of the spectral resonances can be seen better in the HNGD spectrogram.

2.2. Dynamics of coupling of oral and nasal tracts

The phenomenon of nasalization is categorized into three major types [21]:

- Co-articulatory nasalization: The cases where nasal consonants appear either in the pre-vocalic or post-vocalic or both contexts with a vowel. Production of a nasal requires complete closure of the oral tract. Delay in the closure of the oral tract, while opening the velopharyngeal section, leads to nasalization of the vowel preceding a nasal consonant. On the other hand, opening of the oral tract before closure of the velopharyngeal section leads to nasalization of the vowel following a nasal consonant.
- Phonemic nasalization: The cases where vowels are distinctively nasalized, independent of any contextual proximity to nasals. Oral and nasalized vowels form a minimal pair for such cases, which are

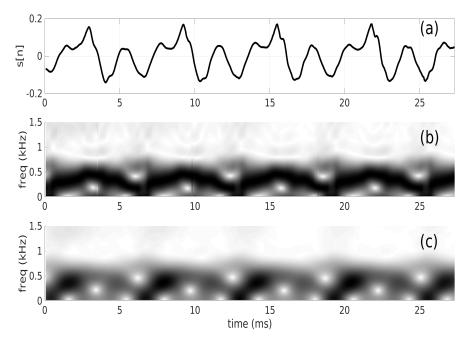


Figure 1: Estimated spectrograms for a vowel segment using ZTW and STFT methods. (a) Segment of speech signal. (b) HNGD spectrogram using ZTW analysis method with l=4 ms. (c) STFT spectrogram using a Hann window of 4 ms.

linguistically different from each other and therefore convey different meaning.

• Functional nasalization: The cases where characteristics of nasalization are introduced in vowels due to dysfunctional velar mechanism.

Co–articulatory nasalization is the most dynamic of the three types of nasalization discussed above, in terms of production system complexity, duration, dependence on factors related to contextual load, muscular inertia, articulatory constraints, speaking rate etc. Vowels appearing in context of nasal consonants are expected to be nasalized, at least for part of their duration. This assumption may hold true across different utterances and speakers in different languages. Furthermore, the degree of nasalization may also vary for different utterances of same VC/CV pair.

Recent studies show that acoustic correlates A1-P1 and A1-P0 are popular in detecting the presence of nasalization in vowels [22]. However, derivation of these parameters requires manual demarcation of locations of F0, P0 and P1 in STFT, which is a tedious process. Furthermore, the harmonic structure of spectrum and the analysis window response pose difficulty in resolving the nasal formant and other spectral peaks in STFT. The

dominant resonance frequency (DRF) contour derived from the HNGD spectra are therefore utilized to identify the presence of nasal resonance in vowel spectra. DRFs have proven to be a consistent and concise representation of the spectral characteristics in speech, and efficiently reflect changes in production system due to coupling/decoupling of cavities to the oral tract [20]. Ability of DRFs to capture distinction in the production system response for oral and nasalized vowels also serves as motivation to this study.

3. Analysis of oral and nasalized vowels using DRFs

The section describes behavior of DRF contours for oral vowels and nasal segments. The behavior is further investigated for nasalized vowel segments. Previous studies hypothesized that vowels present in these contexts are always nasalized. The present section investigates the behavior of DRFs in oral vowels and nasal segments. A hypothesis is suggested on the basis of this behavior, to study the behavior of DRF contour during vowel nasalization. This hypothesis is validated based on previously proposed spectral correlates. The validation is conducted for vowels in English language, obtained from utterances recorded by male and female speakers of English language in TIMIT database [23].

3.1. Distinction in behaviour of DRFs for oral vowel and nasal segments

Distinction in the spectral structure among nasal and oral vowel segments has been widely discussed in literature. Presence of a characteristic resonance in lower frequencies, and a spectral null following it, is attributed to the presence of a longer nasal cavity coupled with a closed oral cavity, during production of nasals. Production of oral vowels is usually characterized by spectral resonances in relatively higher frequency range. These spectral characteristics are derived at a frame duration 20–30 ms with an underlying assumption of stationarity of the production system. Such analysis averages the behavior of speech production system, which otherwise is continuously changing in nature.

The present study uses HNGD spectrum, obtained over short duration of 4 ms, to derive the DRF contours reflecting instantaneous changes in production system response. The glottal activity during production of oral and nasal vowels leads to a fluctuation of DRFs within high and low frequency range for each glottal cycle [20]. These fluctuations are characterized using mean (μ_D) and standard deviation (σ_D) derived over the DRF contour across

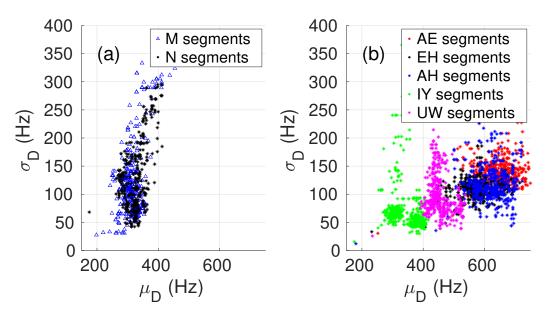


Figure 2: μ_D vs σ_D across glottal cycles for (a) nasal consonants /m/ and /n/, and (b) vowels $/\approx$ /, $/\approx$ /, $/\approx$ /, $/\approx$ /, $/\approx$ /, $/\approx$ /, $/\approx$ /.

every glottal cycle, for vowel and nasal segments. μ_D indicates the centroid and σ_D indicates the bounds of fluctuation in DRF contours for respective utterances. Fig. 2 shows the distribution of these values in spectral plane, obtained over multiple instances of oral vowel and nasal segments in continuous speech in English language, for utterances chosen from TIMIT dataset [23]. Fig. 2(a) gives location of μ_D vs. σ_D values for nasal (/m/ and /n/) segments, and Fig. 2(b) gives these for oral vowel (/æ/, /e/, /a/, /i/, and/u/) segments. Oral vowels are chosen as vowel segments appearing in context with fricative and stop consonants. Except for /i/, the non-overlapping clusters for oral vowels and nasals show distinction in the production system characteristics for oral vowels and nasals. Literature have highlighted the difficulties in identifying nasalization within front vowels [11]. Thus, the study will not cover instances of /i/ for analysis. For other oral vowels and nasals, clusters of μ_D vs. σ_D help in deriving bounds for the expected range of occurrence and fluctuations of DRF contours. Given the figure, the 300-400 Hz range (= B_N) is understood as expected range of fluctuation of DRF contour for nasal segments (Fig. 2 (a)), and the 450–850 Hz range (= B_V) for oral vowels (Fig. 2 (b)).

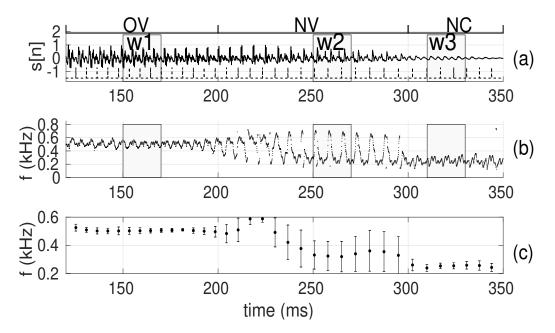


Figure 3: DRF contour obtained for VC transition segment. (a) Speech with the GCI locations (dotted). (b) DRF contour. (c) μ_D (dots) and σ_D (bars) within each glottal cycle.

3.2. DRF contour for vowels appearing in nasal context

Vowels appearing in CV/VC context with nasal consonants experience a contextual load, which dictates the graduation of instantaneous spectral behavior from B_V to B_N , towards the conjunction boundary of these segments. A sudden transition reflects the absence of overlap of their respective spectral characteristics. A gradual transition of DRFs within B_V , towards the characteristics of B_N , within the vowel segment indicates an overlap of nasal spectral characteristics. Fig. 3 illustrates one such example of graduation in DRF contour across the length of a vowel segment, present with a nasal context. Fig. 3(a) shows the signal for a VC pair /æ/ and /n/, in the utterance 'man' spoken by a female speaker of English language. The DRF contour obtained from the HNGD spectra using the ZTW method with an analysis window of 4 ms is shown in Fig. 3(b). The VC boundary appears at 300 ms as given by the annotations provided with the database. Changes in the behavior and fluctuations of DRF contour across the length of vowel can be noted in the figure. Glottal cycles are identified using glottal closure instants (GCIs) derived using ZFF method [18] (Fig. 3(a)).

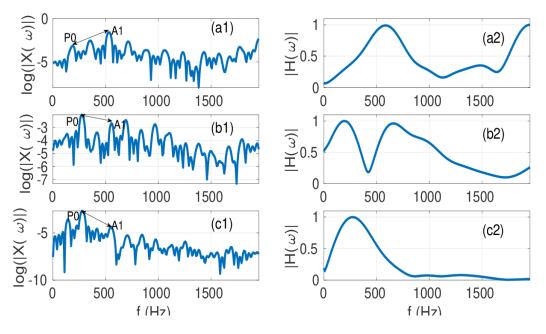


Figure 4: Comparison of DFT and HNGD spectra for OV, NV and NC segments. (a1), (b1) and (c1) DFT spectra in OV, NV and NC regions, respectively, with the A1-P0. (a2), (b2) and (c2) HNGD spectra.

Three locations, w1 (near the vowel onset), w2 (near the VC conjunction region), and w3 (post the conjunction region) are chosen to illustrate the distinction and similarity, in spectral behavior across the vowel segment with the nasal spectra, for different instances. The locations, w1 and w2 lie in the vowel segment whereas w3 lies in the nasal segment. Figs. 4(a1), 4(b1) and 4(c1) show the DFT spectrum obtained at w1, w2 and w3 in the segment. The oral formant can be resolved around 550 Hz as the strongest harmonic peak, in Fig. 4(a1), with an amplitude value understood as A1. The characteristic low frequency nasal resonance is resolved around 300-350 Hz, in Fig. 4(c1), with an amplitude value $P\theta$. The parameter $A1-P\theta$ exhibits relatively a higher value at the window location w1 (Fig. 4(a1)) as compared to location w2 (Fig. 4(b1)). The value of $P\theta$ appears larger than A1 for the case of location w2, which is closer to the VC conjunction region, resulting in a negative value of the parameter. Another limitation with the parameter A1-P0, apart from resolving the locations of spectral peaks, is that it needs to be observed in a relative frame of reference. It is therefore difficult to determine the presence of nasalization for segments with few instances of the

same VC/CV pair.

Figs. 4(a2), 4(b2) and 4(c2), show the HNGD spectrum obtained at w1, w2, and w3 using l=5 ms, respectively. The oral and nasal resonances in 550–600 and 300–350 Hz regions are easily resolved in the HNGD spectra in Figs. 4(a2) and 4(b2), respectively. The HNGD spectrum at w2 exhibits both oral and nasal resonances with similar dominant behavior. This asserts the simultaneous presence of both these cavities during the production, which is also verified with a relatively lower value of A1-P0 in this region. The DRF contour in Fig. 3(b) illustrates the distinction in oral and nasalized segments based on the bound of their fluctuation within each glottal cycle. The oral vowel and nasal segments exhibit DRFs in B_V and B_N ranges, respectively, as suggested by the μ_D and σ_D values in Fig. 3(c). The nasalized segments exhibit DRFs fluctuating between B_V and B_N ranges, owing to presence of a coupled oral and nasal tract, leading to a shift in μ_D and higher σ_D values. Due to a high temporal resolution, it is easier to demarcate the presence of nasalization for each glottal cycle with an improved accuracy.

4. Behavior of DRF contour for a variability in coupling of oral and nasal tracts

DRFs appear as distinctive feature of the HNGD spectrum to represent the instantaneous vocal tract system response. Adduction of the nasal tract to the oral tract results in the dominance of a characteristic low frequency nasal resonance, which is efficiently captured by the DRFs in HNGD spectrum. The presence section studies the characteristics of DRF contours for different cases of oral–nasal coupling. The effect of a higher extent of this coupling on DRF behavior is explored in detail. The section also highlights the importance of segment duration, and hence determination of the glottal open phase, towards identification of nasalization in vowels.

4.1. Behavior of DRF for vowels nasalized at different extents

A significant transition in the behavior of DRFs in vowel segments is illustrated by deviation in their fluctuation from B_V range. There can be several factors to cause such a deviation, but for the study of nasalization in vowels, such a behavior is largely dependent on the extent of coupling of the oral and nasal tracts. Presence of nasalization can easily be tracked using the μ_D and σ_D parameters derived for the DRF contours. A change in the

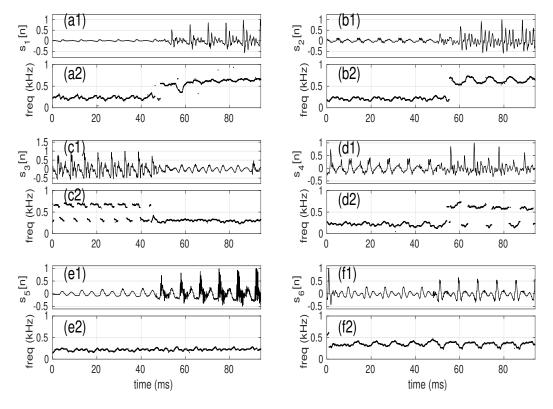


Figure 5: DRF contours obtained using ZTW analysis, for different extents of nasalization. (a1)–(f1) Speech signals for syllable /me/, /ma/, /en/, /ma/, /mi/ and /ni/, respectively. (a2)–(f2) DRF contours for the corresponding signals.

extent of coupling, however, dictates the extent of shift in values of these parameters.

Figure 5 shows the DRF contour for VC/CV segments of English words uttered by different male and female speakers of English, to illustrate the difference in extent of oral–nasal coupling. The different VC/CV pairs in the figures are as follows: Fig. 5(a1) for /me/ (word ' \underline{melody} ', gender: male), Fig. 5(b1) for /ma/ (word ' \underline{monday} ', gender: male), Fig. for 5(c1) /æn/ (word ' \underline{an} ', gender: female), Fig. 5(d1) for /ma/ (word ' \underline{lemon} ', gender: female), Fig. 5(e1) for /mi/(word ' \underline{me} ', gender: male) and Fig. 5(f1) for /ni/ (word ' \underline{money} ', gender: male). The VC/CV transition boundary can be located around $\overline{50}$ ms for all the segments as given by respective annotations. In Figs. 5(a2) and 5(b2), the DRF contours corresponding to oral and nasal segments appear bounded within the B_V and B_N range, respectively. Figs. 5(c2) and 5(d2) show the cases where the DRF contours for vowel segments, fluctuate between the B_V and B_N range. This reflects the simultaneous dominance of oral and nasal resonances, and hence the vowel is hypothesized as partially nasalized.

Figs. 5(e2) and 5(f2) show the DRF contours appearing completely in the B_N range for the vowel segment, with a behavior similar to nasal segment. The VC/CV transition boundaries occur around 50 ms (Figs. 5(e1) and 5(f1)), which cannot be observed in the respective DRF contours. This behavior reflects the presence of a dominant nasal resonance for the entire duration of vowel segment, which is attributed to a larger extent of coupling of oral and nasal tracts. Such a coupling masks oral resonance, and hence the DRF contours shift completely towards B_N range. The following Secs. 4.2 and 4.3 present further discussions on this.

4.2. Significance of glottal open region for studying degree of nasalization

Relation between glottal open phase and degree of nasalization, with a higher open quotient leading to a higher degree of nasalization, has been studied in literature [11]. It has also been reported that spectral behavior for a nasalized vowel is similar to addition of the transfer function of oral and nasal cavities, along with a shift and broadening of the formant peaks [24]. The present section examines these factors, based on the behavior of DRF contour in nasalized vowel segments.

Fig. 6 illustrates a case of partial extent of nasalization of a vowel segment. Once again, this claim of extent is based on the behavior of DRF contour which fluctuates between B_V and B_N range. Fig. 6(a) shows the speech signal along with the GCI locations for the VC segment (/on/ word: 'only' in English language, uttered by English male speaker). Fig. 6(b) shows the DRF contour obtained from the HNGD spectra with l=6 ms. The regions of nasal consonant (NC), nasalized vowel (NV) and oral vowel (OV) segments are marked manually across the CV segment based on the DRF contour behavior, with NV exhibiting a partial degree of nasalization in 70–130 ms duration. The B_V and B_N ranges can be identified from OV and NC segments in range 500–650 Hz and 200–400 Hz, respectively. A close observation suggests that the DRFs in vicinity of GCIs appear in the B_V range, whereas those in the middle of two GCI locations appear transit to the B_N range.

Fig. 6(c) shows a magnified view of the DRF contour for the segment from OV and NV regions, in 10–100 ms duration. The figure also marks two regions R1 and R2 within OV and NV regions, demarcated manually, which essentially span from the onset of the glottal open phase to part of the close phase, as derived by the behavior of DRF contour [20]. These regions are identified to illustrate the evolution of spectral behavior across a glottal cycle

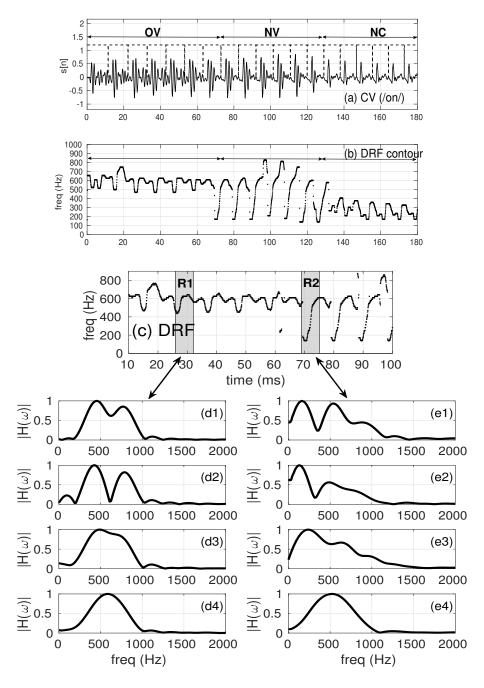


Figure 6: Illustration of DRF contours and HNGD spectra for the partial opening of the velopharyngeal port during the production of the vowel segment. (a) speech signal for VC /on/ (word: only) with GCI. (b) DRF contour. (c) Magnified DRF contour from 10–100 ms with analysis regions R1 and R2. (d1)–(d4) HNGD spectra at equidistant windows in region R1. (e1)–(e4) HNGD spectra for equidistant windows in region R2

for OV segments, and NV segments owing to a partial degree of nasalization. The closed region behavior is nearly identical for both OV and NV segments. The spectrum within R1 and R2, sampled at four equidistant locations, is showed in Figs. 6(d1)–(d4) and 6(e1)–(e4), respectively. Figs. 6(d1)–(d2) correspond to glottal open region for R1. A spectral dominance can be noted around 450 Hz, which further can be seen shifting to higher frequency range ($\sim 600 \text{ Hz}$) during the glottal closed phases, in Figs. 6(d3)–(d4). During the glottal open phase for OV segments, this close phase resonance shifts to a higher 700–750 Hz as a secondary peak, in Fig. 6(d2).

A shift in location of oral vowel formants during nasalization has already been discussed in the literature [11]. Figs. 6(e1)–(e4) show the spectral evolution during R2, present in NV segment. Dominance of low frequency characteristic nasal resonance at 200 Hz during glottal open phase (Figs. 6(e1)–(e3)), along with the shifted oral resonance (~ 600 –800 Hz) impress upon the coupling of oral and nasal tracts. The dominant behavior of the low frequency resonance during the glottal open phase transits back to oral formant location during glottal closed phase, in Fig. 6(e4). Similarity in DRF during glottal closed phase for OV and NV segments can be noted in Figs. 6(d4) and 6(e4). The oral resonances are weaker and hence masked by presence of a stronger nasal zero in the vicinity of first formant, during low SNR glottal open phase. The figure illustrates the alternating dominance of oral and nasal resonances for a partial extent of nasalization. This verifies the hypothesis of a partial coupling of oral–nasal tracts, as claimed earlier for Figs. 5(c2) and 5(d2).

The effect of analysis window duration on identification of glottal open and closed phases in speech has been discussed in the literature [20]. The dominant resonances during the glottal open phase are weaker and hence are masked if the size of the analysis window is longer than few pitch periods. It is therefore necessary to maintain the analysis window duration comparable to the pitch duration to study nasalization in vowels.

4.3. Full extent of coupling of oral-nasal tracts

It has been discussed in the literature that a higher extent of coupling of oral—nasal tracts has a more drastic effect on the vowel spectra [24]. A larger opening of the velopharyngeal section results in a stronger nasal resonance which dominates the oral resonance during entire glottal cycle. Oral resonance experiences significant decay due to a higher extent of coupling. Fig. 7 illustrates this phenomenon with the help of strength of resonances.

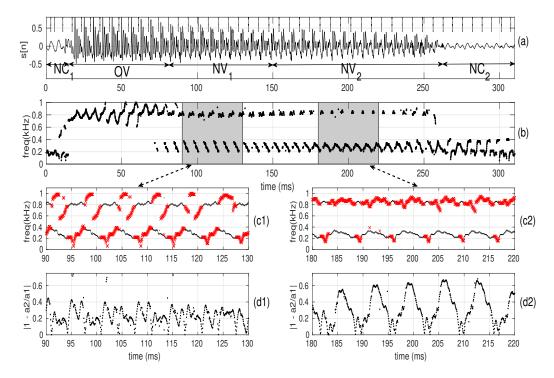


Figure 7: DRF and DRF₂ contours illustrating the variation in degree of coupling of nasal and oral tracts. (a) Speech segment with the GCI locations (dotted). (b) DRF contour. (c1) and (c2) DRF (solid line) along with DRF₂ (**). (d1) and (d2) |1 - a2/a1|.

Fig. 7(a) shows a vowel segment /æ, present in context of nasal consonants /m and /n (word: ' \underline{man} ' in English language by a female English speaker). The GCI locations for the segment are shown by dotted vertical lines, along with demarcations for nasal segments (NC₁ and NC₂), oral vowel (OV) and nasalized segments (NV₁ and NV₂). Fig. 7(b) shows the DRF contour for the segment obtained using the ZTW method with l = 6 ms. DRFs in NC₁ and NC₂, and OV segments appear in B_N and B_V range.

The NV₁ and NV₂ segments (80–260 ms duration) are nasalized. Splitting of nasalized vowel segment within NV₁ and NV₂ is done to illustrate the difference of extent of coupling of oral–nasal tracts. Regions within NV₁ and NV₂ are chosen to illustrate the difference in behavior of DRF contour for different extent of nasalization. Figs. 7(c1) and 7(c2) show the DRF (solid line) and DRF₂ (**) contours within NV₁ and NV₂ segments, respectively. The DRF₂ are the secondary dominant resonances in the spectrum and are used in this context to illustrate the shift in dominance. These are identified as resonances with strength next to DRF in the HNGD spectrum. Figs. 7(d1) and 7(d2) show the relative difference ($\alpha = |1 - (a2/a1)|$) of amplitudes a1 and a2 of DRF and DRF₂, respectively, within NV₁ and NV₂ segments, respectively.

The NV₁ segment exhibits a partial extent of nasalization as suggested by the DRF contour. The DRF₂ contour (Fig. 7(c1)) appears appropriately in the gaps in DRF contour, suggesting the simultaneous presence of resonances in B_V and B_N range, across the vowel segment. DRF contour in NV₂ segment shifts completely to B_N range reflecting the increased dominance of nasal resonance over the oral resonance. The DRF₂ also shifts appropriately to B_V range (Fig. 7(c2)). Average value of α can also be observed rising with each glottal cycle while transiting from NV₁ to NV₂ segments (Fig. 7(d2)). This reflects a stronger nasal resonance compared to the oral resonance in NV₂ segments. A stronger nasal characteristic resonance within vowel segments signifies a larger extent of velopharyngeal opening.

5. Observations at CV/VC boundaries for vowel–nasal pairs

The section validates the relation between σ_D and A1-P0 for different sets of oral and nasalized vowels. The section also examines the presence of nasalization owing to co–articulatory load across multiple instances of CV/VC and CVC utterances in English.

5.1. Relation in A1-P0 and σ_D

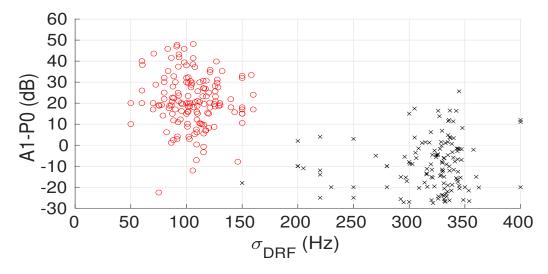


Figure 8: $A1-P\theta$ vs σ_{DRF} for OV (\circ) and NV (\times) segments.

Values of A1-P0, and their relation with σ_D values, is explored for OV and NV segments in TIMIT database [23]. The OV and NV segments are

identified using the proposed hypothesis based on the DRF contours. Fig. 8 gives values obtained for A1-P0 against σ_D for different OV and NV segments obtained across several speakers in TIMIT. The OV segments are obtained from vowels appearing in CV/VC clusters with fricative or stop consonants. The NV segments are obtained from vowels appearing in context of a nasal consonant with their DRFs fluctuating to B_N range. The A1-P0values are derived over a 20 ms frame duration at VC/CV transition region for vowel segments. Peaks corresponding to A1 and P0 are marked manually in the normalized log spectrum obtained using DFT. σ_D values obtained with ZTW using analysis window of 4 ms, are averaged across a duration of 20 ms at VC/CV transition boundary. It is observed that $A1-P\theta$ values for oral vowel segments (o) are higher and positive. This signifies a stronger F_1 as compared to low frequency resonance. The corresponding σ_D values are also found to be relatively lower ($\sim 70-130~\mathrm{Hz}$). The NV segments on the other hand, result in negative $A1-P\theta$ values (\times) appearing in distinct cluster. Values of σ_D are also relatively higher ($\sim 320-360~{\rm Hz}$) for NV segments. These two non-overlapping clusters suggests that proposed analysis aligns with previously suggested spectral correlates to capture nasalization in vowels. The proposed method based on DRF contour however, reflects the spectral information at a better resolution, and makes it relatively easier to be characterised. .

5.2. Study of vowels at VC/CV transition boundaries

The proposed method is employed to examine the behavior of vowel segment at CV/VC transition boundaries when present in context with nasal consonants. The μ_D and σ_D values are derived from DRF contours, obtained using ZTW analysis with $l=5 \mathrm{ms}$. The VC/CV segments are obtained from utterances by different male and female speakers in TIMIT. Values of μ_D and σ_D , averaged across a duration of 5 glottal cycles in the vowel segment, at the CV/VC transition boundary are reported. Figs. 9 and 10 show observations for vowels /æ/ and /y/ present in context with nasal consonants /m/ and /n/, in utterances obtained across different speakers.

Few segments exhibit a similarity in behavior for μ_D values, in /æ/, where these values are present in the range B_V , as seen in Figs. 9(a1)–9(b2). Some of these values for /v/, especially for VC transition, appear in range B_N which shows the affinity of this vowel to get nasalized, as seen in Figs. 10(a2)–10(b2). Few instances for /æ/ at VC boundary with /m/ (Fig. 9(a1)) show increased value of σ_D , which also illustrates the overlap of B_V

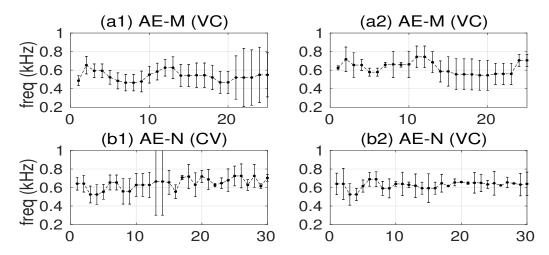


Figure 9: Errorbars for average μ_D and σ_D values obtained across VC/CV boundaries for vowel /æ/.

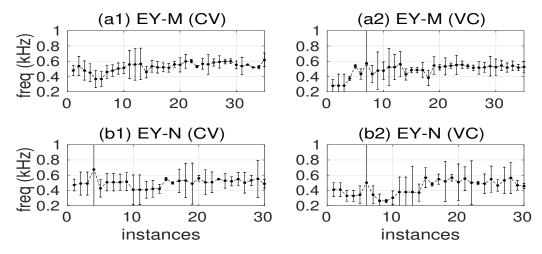


Figure 10: Errorbars for average μ_D and σ_D values obtained across VC/CV boundaries for vowel /y/.

and B_N and hence presence of nasalization. The figures illustrate a dynamic nature of nasalization due to contextual load across similar CV/VC clusters, for different speakers.

6. SUMMARY

This paper presents a new way to study the phenomena of nasalization of vowels based on dominant behavior of the instantaneous spectral characteristics. The problems of identification of duration and extent of nasalization in vowels are addressed in this paper. The DRFs obtained from HNGD spectrum fluctuate within characteristic B_V and B_N range for oral vowels and nasal consonants, respectively. Changes in the spectral structure of vowels due to coupling of oral-nasal tracts are captured based on the average location and spread of DRFs. This behavior is characterized across each glottal cycle using the μ_D and σ_D parameters. A partial extent of nasalization examined across glottal open and closed phase, and is illustrated through fluctuations in DRFs within B_V and B_N range. The paper also explains the shift in dominance within oral and nasal resonances across glottal phases, for a partial nasalization. A higher extent of coupling is illustrated by a stronger nasal resonance dominating across the entire glottal cycle. Examination of secondary dominant resonance proves a continuum in DRF contours in B_V and B_N range during nasalization. Comparison of strengths of DRF and DRF₂ shows the transition of dominance within oral and nasal resonances.

The study is carried out over nasal–vowel pairs occurring words in the English language, spoken by different male and female English speakers. The behavior of σ_D for nasalized vowel segments is also validated using spectral correlate A1-P0 derived across VC/CV boundaries. The DRF₂ contour helps to illustrate the simultaneous presence of oral and nasal resonances in the spectrum for nasalized vowels, and the fluctuation in the dominant behavior between the two. The study can easily be implemented across different languages and speakers, and can help in studying speech pathology.

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