# 비대칭 4 질량 성대 모델에 의한 쉰목소리 분석

# Hoarse Speech Analysis
# Using Dissymmetric Four-Mass Model of Vocal Cords

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## ABSTRACT

In this paper, a new vocal cords model, called a four-mass model, is proposed for a hoarse speech mechanism. Pathological changes of vocal cords cause hoarse speech and glottal waveform reflects motion states of vocal cords. From these facts, we assumed that the morbid vocal cords be dissymmetric and take the four-mass type. The glottal waveforms and the model parameters of normal and hoarse speech signals are analyzed, and some relations between the model parameters and the hoarse pathology are discussed. Experimental results show that the new research method of hoarse speech can reveal relations between the acoustic features of hoarse speech and the hoarse pathology, and be used to diagnose laryngeal diseases and to improve tone quality of hoarse speech.

## 요 약

본 논문에서는 쉰 목소리 메커니즘 분석을 위한 4질량 성대 모델을 제안하였다. 쉰 목소리가 성대의 병리학적 변화에 기인한다는 것과 성문 파형이 성대의 움직임 상태를 반영한다는 사실에서, 병든 성대를 비대칭 구조이고 4 질량형으로 가정하였다. 정상 목소리와 쉰 목소리에 대한 모델 변수들과 성문 파형을 분석하여 모델 변수와 병리학 사이의 관계를 검토하였다.

실험 결과 쉰 목소리의 음향 특징과 병리학간의 관계를 밝힐 수 있었고 후두 질병 진단과 쉰 복소리의 음질 향상에도 본 논문에서 제안한 방법이 사용될 수 있음을 알았다.

## Ⅰ. INTRODUCTION

Analysis of hoarse speech signal is an efficient method to research diagnosis of laryngeal diseases, and is quite significant for improving quality of speech communication. speech recognition, speech synthesis, man-machine dialogue, and other speech productions. The main acoustic detection means of laryngeal diseases were acoustic spectrum analysis, electric glottal-graphy, and so on [1, 2]. Spectrogram is used to analyze speech signals by displaying the relations between sound intensity, frequency and time. Spectrograms of normal speech display the regularity and consistence of longitudinal spectral lines, while hoarse speech spectrograms have much spectral noise and confusion of spectral lines. Electric glottal-graphy can reflect acoustic resistance of the glottis to a certain extent. In last decades, a single mass model of vocal cords for voice signal was built by Flanagan et al. [3], which has been improved and developed in [4-7]. Recently, three-

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mass model of vocal cords has been used to analyze hoarse speech signals by speech synthesis [8]. It has also been proposed that periodic difference, vibration amplitude and disturbance coefficient of the glottal waveform are used to express features of hoarse speech signals [9], while the glottal waveforms can be exactly estimated from speech signals [10].

It is well-known that vocal cords are the basis of speech generation and the glottal waveform reflects the situation of vocal cords motion [9, 11, 12]. In this paper, for analysis of hoarse speech signals, we have mainly developed dissymmetric four-mass model of vocal cords and analysis of the glottal waveform. Inharmony of vocal cords vibration, which is caused by local pathological changes of vocal cords, is researched, and mechanisms of hoarse speech generation and morbid vocal cords are analyzed. Relations between parameters of the model, local pathology of vocal cords and the glottal waveform of hoarse speech signal are obtained, and the acoustic natures of hoarse speech signals can be grasped better by the new method.

## Ⅱ. DISSYMMETRIC FOUR-MASS MODEL OF VOCAL CORDS

### 2.1 Dissymmetric four-mass model of vocal cords and network model of vocal system

The conventional models of vocal cords, such as two-mass model and three-mass model, are difficult to represent exactly the local pathological changes of vocal cords because they are assumed to be symmetric in depth of glottis. Therefore, they can not characterize sufficiently hoarse speech signals which are mainly caused by the pathological changes of vocal cords. To overcome the problem of symmetric structure in the conventional models, a dissymmetric four-mass model of vocal cords for voice signal is developed as shown in Fig. 1 in this paper. In Fig. 1, the left pipe represents the trachea, leading to the lung, and its pressure is $P_s$. The right represents the larynx tube, leading to the vocal tract. Two lateral cords in the model are not symmetric because of the pathological changes of vocal cords. Each lateral cord is divided by two parts in depth, and each part accords to a simple mechanical oscillator with a mass, spring, and damping. It is assumed that adjacent masses are coupled with a linear spring and each mass has only lateral motion. Parameters of the new model are defined as

$r_i$, $s_i$, $d_i$ : equivalent viscous damping, equivalent nonlinear spring, and thickness of each mass $m_i$ ($d_1 = d_3$, $d_2 = d_4$),

$k_{ij}$ : equivalent linear coupling spring of $m_i$ and $m_j$,

$A_i$, $A_{gi}$ : input area to the vocal tract and cross sectional area between $m_i$ and $m_{i+2}$,

$U_g$ : average glottal volume velocity,

$\mu$ : shear viscous coefficient,

$l_g$, $l_c$, $l_e$ : effective length of the glottal slit, the contraction between the trachea and the vocal cords, and the contraction between the vocal cords and the larynx tube.

To obtain an equivalent circuit of the glottis and a network model of the vocal system for hoarse speech, we now analyze the dissymmetric four-mass model of vocal cords in Fig. 1.

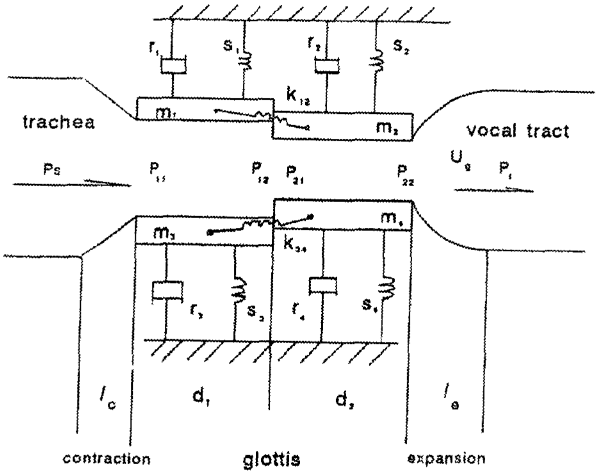

Fig. 1 Proposed dissymmetric four-mass model of vocel cord

### 1. Equivalent stiffness characteristics of vocal cords muscle

The force $f_{si}$ required to produce the displacement of the mass $m_i$ is given by

$$f_{si} = k_i(x_i - x_{0i})(1 + \eta_{ki}(x_i - x_{0i})^2) \tag{1}$$

where $k_i$ is the equivalent linear stiffness, $\eta_{ki}$ is the nonlinear coefficient of spring $s_i$($\eta_{ki} > 0$), and $x_{0i}$ is the static position of the mass $m_i$.

When the opposing masses collide during the closure of the glottis, the force $f_{hi}$ required to produce the deformation to mass $m_i$ is given by

$$f_{hi}=0.5h_i(x_i+x_j)(1+0.25\eta_{hi}(x_i+x_j)^2) \qquad (2)$$

where $x_i+x_j \leq 0$, when i is 1 or 3, then j is 3 or 1; when i is 2 or 4, then j is 4 or 2. And $h_i$ is the linear stiffness, $\eta_{hi}$ is the nonlinear coefficient representing the nonlinearity of the contacting vocal cords ($\eta_{hi} \geq 0$).

The resultant restoring forces acting on the mass $m_i$ is the sum of $f_{si}$ and $f_{hi}$.

Additionally, the equivalent viscous damping, $r_i$, is $2\xi_i\sqrt{m_ik_i}$, where $\xi_i$ is the damping ratio.

2. Pressure drop of the contraction between vocal cords and trachea is $0.69\,\rho\,U_g^2/A_{g1}^2$, where $\rho$ is the air density.

3. Pressure drop along with the depth of the vocal cords

The pressures in the depth of $d_1$ and of $d_2$ fall linearly along with $12\mu d_1 l_g^2/A_{g1}^3$ and $12\mu d_1 l_g^2/A_{g2}^3$, respectively.

4. Pressure drop at the junction between a mass and its adjacent mass is

$$0.5\rho U_{g2}(1/A_{g2}^2-1/A_{g1}^2).$$

5. Pressure change at the junction between vocal cords and larynx tube is

$$-\rho\left(\frac{U_g}{A_{g2}}\right)^2\left(1-\frac{A_{g2}}{A_1}\right)\frac{A_{g2}}{A_1}$$

6. The pressure distribution along the glottis is given by

$$P_s-P_{11}=0.685\rho\left(\frac{U_g}{A_{g1}}\right)^2+\int_0^{l_c}\frac{\rho}{A_c(x)}\frac{dU_g}{dt}dx \qquad (3)$$

$$P_{11}-P_{12}=\frac{12\mu l_g^2 d_1}{A_{g1}^3}U_g+\frac{\rho d_1}{A_{g1}}\frac{dU_g}{dt} \qquad (4)$$

$$P_{12}-P_{21}=0.5\rho U_g^2(1/A_{g2}^2-1/A_{g1}^2) \qquad (5)$$

$$P_{21}-P_{22}=\frac{12\mu l_g^2 d_2}{A_{g2}^3}U_g+\frac{\rho d_2}{A_{g2}}\frac{dU_g}{dt} \qquad (5)$$

$$P_{22}-P_1=-\rho\left(\frac{U_g}{A_{g2}}\right)^2\frac{A_{g2}}{A_1}\left(1-\frac{A_{g2}}{A_1}\right) \qquad (7)$$

where $A_{g1}=l_g(x_1+x_3)$, $A_{g2}=l_g(x_2+x_4)$.

7. Equivalent circuit of the glottis and network model of the vocal system for voice signal

On the basis of the pressure difference relations discussed above, the acoustic impedance elements of the glottis constitute the equivalent circuit shown in Fig. 2. The acoustic impedance elements are given by

$$R_c=0.685\,\rho\frac{|U_g|}{A_{g1}^2}, \qquad L_c=\int_0^{l_c}\frac{\rho\,dx}{A_c(x)},$$

$$R_{v1}=12\frac{\mu l_g^2 d_1}{A_{g1}^3}, \qquad L_{g1}=\frac{\rho d_1}{A_{g1}},$$

$$R_{12}=0.5\rho|U_g|\left(\frac{1}{A_{g2}^2}-\frac{1}{A_{g1}^2}\right), \qquad L_{g2}=\frac{\rho d_2}{A_{g2}},$$

$$R_{v2}=12\frac{\mu l_g^2 d_2}{A_{g2}^3}. \qquad R_e=-\frac{\rho|U_g|}{A_{g2}A_1}\left(1-\frac{A_g}{A_1}\right).$$

The total acoustic impedance of the glottis, $Z_g$, is

$$Z_g=(R_c+R_{12}+R_e)+(R_{v1}+R_{v2})+jw(L_c+L_{g1}+L_{g2}) \qquad (8)$$

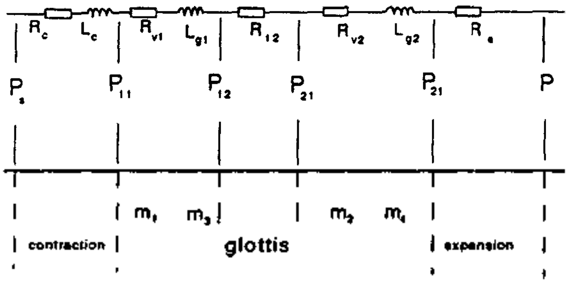

Fig. 2 Equivalent circuit of the glottis

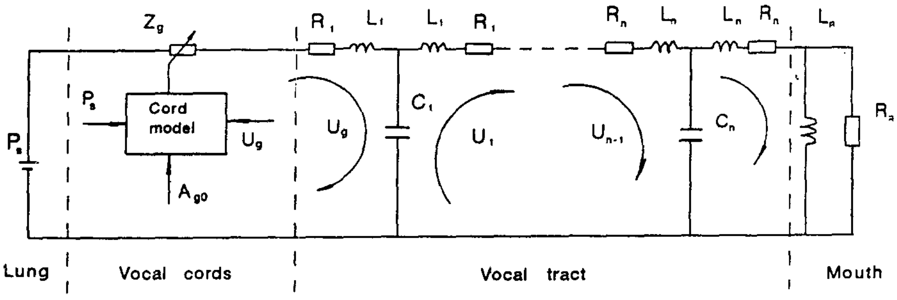

Fig. 3 Network model of the vocal system for voice signal

Fig. 3 shows a network model of the vocal system for voice signal, including subglottis, vocal cords, vocal tract, and mouth. The subglottis is regarded as constant pressure source, $P_s$. The vocal tract is approximated by finite cylindrical acoustic pipes. Let $l_n$, $A_n$, and $S_n$ be the length, the cross-sectional area, and the perimeter of the n-th cylindrical acoustic pipe, respectively. Then, $L_n = 0.5\rho l_n / A_n$, $R_n = (S_n / A_n^2)\sqrt{0.5w \mu\rho}$, $C_n = l_n A_n / (\rho c^2)$, where w is the radial frequency and c is the acoustic velocity. Radial load in the mouth is equal to that for a circular piston in an infinite baffle, namely, $R_R = 128\ \rho c / (9\pi^2 A_R)$ and $L_R = 8/(3\pi\sqrt{\pi A_R})$, where $A_R$ is the mouth area. Finally, relevant circuit equations can be extracted by circuit analysis method.

8. Relation between the displacement and the force

Average pressures acting on $m_1$ and $m_3$, and $m_2$ and $m_4$, denoted $P_{m1}$ and $P_{m2}$, respectively, are given by

$$P_{m1} = P_s - (R_c + 0.5R_{v1})U_g - 0.5L_{g1}\frac{dU_g}{dt} \tag{9}$$

$$P_{m2} = P_{m1} - 0.5(R_{v1} + R_{v2})U_g + (L_{g1} + L_{g2})\frac{dU_g}{dt}\ ) - R_{12}U_g \tag{10}$$

Average forces acting on $m_1$ and $m_3$, and $m_2$ and $m_4$, denoted $F_1$ and $F_2$, respectively, are given

$$F_1 = P_{m1} l_g d_1 \tag{11}$$

$$F_2 = P_{m2} l_g d_2 \tag{12}$$

Table 1 gives the relations between the displacements and the forces.

Table 1 *Relations Between the displacements and the forces*

| $x_1 + x_3$ | $x_2 + x_4$ | $F_1/l_g d_1$ | $F_2/l_g d_2$ |
|---|---|---|---|
| $x_1+x_3>0$ | $x_2+x_4>0$ | $P_{m1}$ | $P_{m2}$ |
| $x_1+x_3>0$ | $x_2+x_4\leq 0$ | $P_S$ | $P_S$ |
| $x_1+x_3\leq 0$ | $x_2+x_4>0$ | $P_S$ | 0 |
| $x_1+x_3\leq 0$ | $x_2+x_4\leq 0$ | $P_S$ | 0 |

9. Motions of the masses can be described by following equations

$$m_1\frac{d^2x_1}{dt^2} + r_1\frac{dx_1}{dt} + S_1(x_1) + k_{12}(x_1 - x_{10} - x_2 + x_{20}) = F_1 \tag{13}$$

$$m_2\frac{d^2x_2}{dt^2} + r_2\frac{dx_2}{dt} + S_2(x_2) + k_{12}(x_1 - x_{10} - x_2 + x_{20}) = F_1 \tag{14}$$

$$m_3\frac{d^2x_3}{dt^2} + r_3\frac{dx_3}{dt} + S_3(x_3) + k_{34}(x_3 - x_{30} - x_4 + x_{40}) = F_2 \tag{15}$$

$$m_4\frac{d^2x_4}{dt^2} + r_4\frac{dx_4}{dt} + S_4(x_4) + k_{34}(x_3 - x_{30} - x_4 + x_{40}) = F_2 \tag{16}$$

where if $x_i + x_j > 0$, then $S_i(X_i) = f_{si}$ ; if $x_i + x_j \leq 0$, then $S_i(x_i) = f_{si} + f_{hi}$.

### 2. 2 Hoarse degree of hoarse speech signal

A minimum short-time square difference function and a period difference of the glottal waveform are introduced as the features to analyze hoarse speech signals. The short-time square difference function of glottal waveform, $M_D$, is defined by

$$M_D(n) = \sum_{m=1}^{M}(U_g(m+1) - U_g(m+1+n))^2 / \sum_{m=1}^{M} U_g(m) \tag{17}$$

where M is an integer larger than the period of the glottal waveform N. $M_D(N)$ is the minimum of $M_D(n)$. The minimum short-time square difference function of the glottal waveform, $M_{DT}$, is given by

$$M_{DT} = \frac{1}{N}\sum_{i=1}^{N} M_D(i) \tag{18}$$

The mean of the periods of the glottal waveform $T_r$ and the period difference of glottal waveform $T_D$ are given by

$$T_r = \frac{1}{L}\sum_{i=1}^{L} T(i) \tag{19}$$

$$T_D = \frac{1}{LT_r}\sum_{i=1}^{L} T(i) - T_r)^2 \tag{20}$$

where $T(i)$ is a sequence of the period of the glottal waveform $U_g(n)$.

$M_{DT}$, in fact, is a synthetical index of representing the change of shape and amplitude of glottal waveform. The larger are $T_D$ and $M_{DT}$, the worse is the tone quality of speech signal. When the glottal waveforms vary with amplitude but not with shape, $M_{DT}$ and vibration amplitude of the glottal waveform are identical. Hence, it is very appropriate that $M_{DT}$ and $T_D$ are chosen as the features of hoarse speech signals.

### 2.3 Software flow of hoarse speech signal analysis

A block diagram of analysis of hoarse speech signal based on the glottal waveform and the dissymmetric four-mass model of vocal cords is shown as Fig. 4. Speech signals are sampled by 20KHz, and analyzed with *linear predictive coding* (LPC) *to extract the* exact glottal waveform of voice signals. The vocal tract area function is obtained by the vocal tract model and reflection coefficients, and the acoustic impedance. The radiation impedance, the equivalent circuit parameters of the vocal tract, and the glottal volume velocity $U_g(n)$ are obtained. The pressure $P_l(n)$ at the contraction between the glottis and the vocal tract is computed. Then, the multidimensional pure graphic method (MPGM) in computer-aided-design (CAD) technology is used to compute the parameters of vocal cords model.

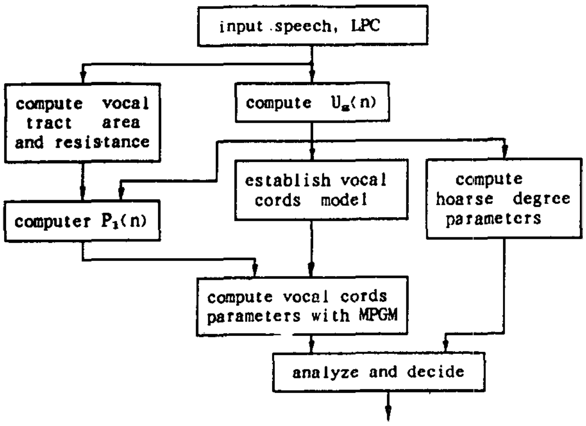

Fig. 4 Block diagram of hoarse speech analysis

The parameters of the vocal cords model can be obtained by the MPGM. The average period of glottal waveform is used to calculate the initial parameters of vocal cords. Parameters of each dimensional pure graphic are computed. $U_{gi}(j)$ is extracted by the circuit in the Fig. 3, and used to compute driving forces, the displacements of masses, and the glottal internal area. The glottal impedance formulation is used to extract new glottal impedance and then the circuit in Fig. 3 are used to calculate $U_{gi}(j+1)$. Repeatedly calculated in this way, $U_{gi}(n)$ and the error $E_{gi}$ between $U_{gi}(n)$ and actual glottal volume velocity $U_g(n)$ can be obtained. When error of each dimension is calculated, the vocal cords parameters corresponding to the maximum of $E_{gi}$ is regarded as a vector to adjust the parameters inversely. Recursively $E_{gi}$ becomes smaller and the vocal cords parameters satisfying the given error condition are finally regarded as the vocal cords parameters of the practical speech signals.

## Ⅲ. EXPERIMENTAL RESULTS AND ANALYSI

With the above-mentioned theory and method, normal and hoarse speech signals are analyzed. In Table 2 and Table 3, group Ⅰ and Ⅱ represent normal speech and hoarse speech for cancer of larynx before operation, respectively, group Ⅲ and Ⅳ represent hoarse speeches for cords paralysis before and after operations, respectively, and group Ⅴ and Ⅵ represent hoarse speeches for vocal cords closed incompletely before and after operations, respectively. Each mass and hoarse degree parameters $T_D$ and $\dot{M}_{DT}$ of speech signals /i/ are shown in Table 2. Equivalent spring stiffness and displacement of mass are shown in Table 3. Since equivalent viscous dampings $r_i$ can be represented by $m_i$ and $k_i$, they are not shown in the tables. The relative difference of weight of mass $\delta_m$ and that of equivalent spring stiffness $\delta_k$ are defined as

$$\delta_m = 100\% \times \sum_{i=1}^{4} |m_i - m_0| / m_0 \tag{21}$$

$$\delta_k = 100\% \times \sum_{i=1}^{4} |k_i - k_0| / k_0 \tag{22}$$

while $m_0$ and $k_0$ are the means of $m_i$ and $k_i$, respectively.

Table 3 Parameters of practical speech signals /i/: $k_i$ and $\delta_k$

| | $k_1$ | $k_2$ | $k_3$ | $k_3$ | $\delta_k$ |
|---|---|---|---|---|---|
| Ⅰ | 56923 | 54872 | 58396 | 57109 | 6.87 |
| Ⅱ | 30667 | 34332 | 30650 | 36916 | 29.97 |
| Ⅲ | 72090 | 81034 | 72364 | 73724 | 16.82 |
| Ⅳ | 62768 | 58687 | 62923 | 58671 | 13.71 |
| Ⅴ | 85019 | 89345 | 80556 | 88416 | 14.20 |
| Ⅵ | 81363 | 85968 | 80806 | 81396 | 8.72 |

Fig. 5 shows normal speech /i/ and its glottal waveform. The glottal waveform of the normal signal

Table 2 Parameters of practical speech signals /i/: $m_i$, $T_D$, $M_{DT}$, and $\delta_m$

| | $m_i$ | $m_2$ | $m_3$ | $m_4$ | $T_D$ | $M_{DT}$ | $\delta_m$ |
|---|---|---|---|---|---|---|---|
| Ⅰ | 0.0709 | 0.0695 | 0.0685 | 0.0680 | 1.359 | 0.0062 | 5.63 |
| Ⅱ | 0.0650 | 0.1226 | 0.0690 | 0.1350 | 2.852 | 0.0098 | 126.25 |
| Ⅲ | 0.0697 | 0.0126 | 0.0714 | 0.0699 | 78.782 | 0.0694 | 99.12 |
| Ⅳ | 0.0829 | 0.0768 | 0.0813 | 0.0771 | 2.382 | 0.0611 | 12.95 |
| Ⅴ | 0.0615 | 0.0611 | 0.0604 | 0.0550 | 2.943 | 0.0084 | 15.13 |
| Ⅵ | 0.0479 | 0.0469 | 0.0466 | 0.0437 | 0.439 | 0.0053 | 10.95 |

manifests a stable periodicity and a suitable proportion of open and close times of the glottis. Each mass is approximately equal to 0.07 gram, stiffness of each equivalent spring is approximately equal to 57 × $10^3$ dyn/cm, and $\delta_m$ and $\delta_k$ are very small, which show that the masses are quite symmetric in the laterals of vocal cords and their differences are also very small in depth of vocal cords for normal speech /i/.

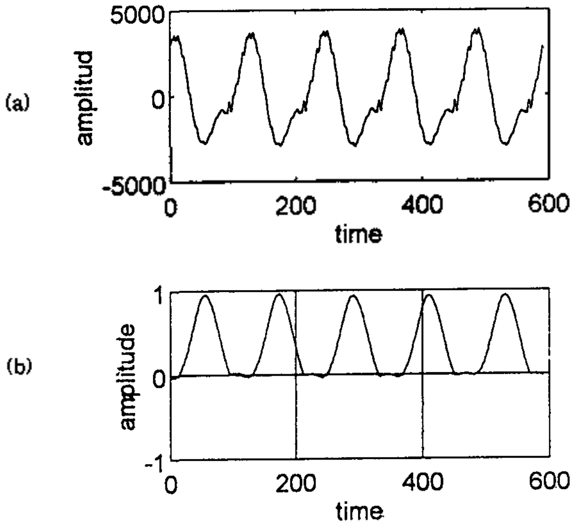

Fig. 5 Normal speech signal /i/ and its glottal waveform
(a) speech signal /i/ (b) its glottal waveform

Fig. 6(a) is glottal waveform of patient with laryngeal cancer before operation, where the glottal waveform appears much noise in the close time of glottis. Its $T_D$ and $M_{DT}$ are both larger than those of normal speech signal, $\delta_m$ and $\delta_k$ are obviously higher than those of normal speech signal. Large $\delta_m$ implies that the difference of weight between the masses are very large ; $m_2$ and $m_4$ are about twice as weighty as $m_1$ and $m_3$, respectively. It is quite obvious that $m_2$ and $m_4$ are in heavily morbid condition. This symptom caused by the laryngeal cancer accords with the result diagnosed by laryngoscope.

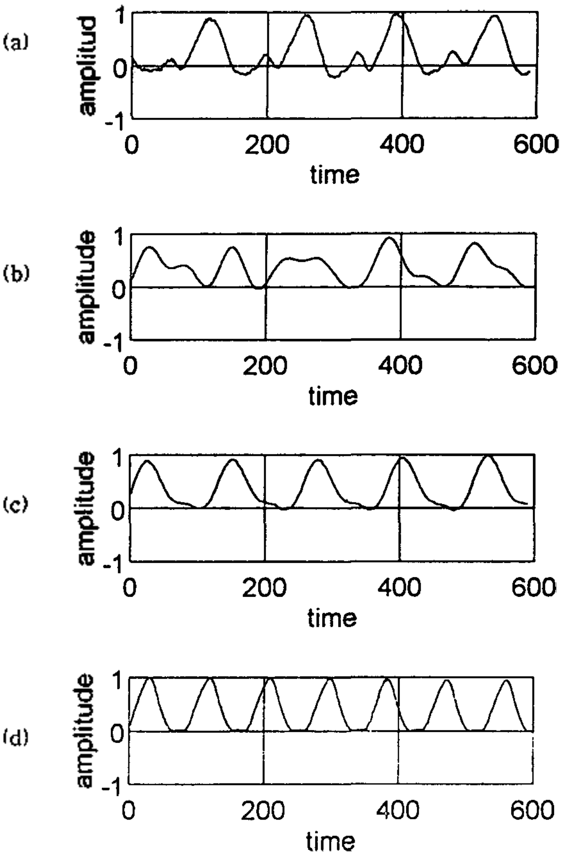

Fig. 6 Glottal wavefroms of hoarse speech signals /i/
(a) Glottal waveform of patient with laryngeal cancer before operation
(b) Glottal wavefrom of patient with cords paralysis before operation
(c) Glottal waveform of patient with cords paralysis after operation
(d) Glottal waveform of vocal cords closed incompletely before operation

Fig. 6(b) and (c) are the glottal waveforms of patient with cords paralysis before and after operations. It is obvious that the periodicity of the glottal waveform of patient with vocal cords paralysis becomes badly poor. $\delta_m$ and $\delta_k$ of cords paralysis patients before operation are larger than those of normal speech signal. $m_2$ and $k_2$ are abnormal comparing with the parameters of other masses ; $m_2$ is very small and $k_2$ is quite large, that is, the natural frequency of the mass $m_2$ is twice higher than those of other masses. Since $k_2$ increases, vibration amplitude of mass $m_2$ decreases, which makes periodicity of the glottal waveform turn poor and $T_D$ and $M_{DT}$ increase. The mass parameters of patient with cords paralysis are improved and become quite similar after operation. $\delta_m$ and $T_D$ are evidently smaller than those before operation and $\delta_k$ decreases.

As to the hoarse speech caused by vocal cords closed incompletely, $T_D$, $M_{DT}$ and the model parameters can not display very evidently abnormal. However, the glottal waveform in Fig. 6(d) can show that vocal cords is open state in the great part of a period of the glottal waveform, and the ratio of close to open times of glottis is about 3 : 7, while the normal ratio of close to open times of glottis is 2 : 3.3. Moreover the static glottal intervals of $m_1$ and $m_3$($A_{g10}$=

0.075cm$^2$) are large. This value is large than that of normal vocal cords, which is 0.02~0.05cm$^2$. After the initial operation, although the ratio of close to open times of the glottis is not improved much more, $M_{DT}$ is improved obviously, and $\delta_m$ and $\delta_k$ decrease. It implies that the model parameters of patients who can not close completely vocal cords are improved after operation.

## Ⅳ. CONCLUSIONS

Because hoarse speech is mainly caused by the pathological changes of vocal cords, the parameters of vocal cords model can represent the physiological mechanism of speech signal. This paper has mainly discussed the hoarse speech signals caused by laryngeal diseases in order to analyze morbid vocal cords. The dissymmetric four-mass vocal cords model is developed and used to analyze the hoarse speech signals since the pathology of vocal cords will result in dissymmetric phenomena of two lateral vocal cords. The relations between model parameters and hoarse pathology are researched. The acoustic features of hoarse speech signals are extracted and analyzed. Some analysis results of hoarse speech signals show that the new analysis method can reveal the relations between the acoustic features of hoarse speech signals and the hoarse pathology, and be used to diagnose laryngeal diseases and to improve the tone quality of hoarse speech.

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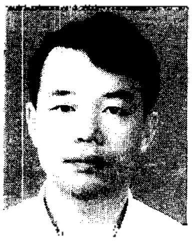

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