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A New Approach on Solving One-Mass Model of Vocal Cord using Hybrid Cubic B-Spline Collocation Method

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ABSTRACT

The vocal cords, also known as vocal folds, are responsible for producing sound and creating the voice. In this work, hybrid cubic B-spline collocation method (HCBs) and ode45 built-in solver in MATLAB were applied to solve one-mass model of vocal cord numerically. From the model, displacements were generated by analysing the voice recording samples of 109 healthy participants. Based on the recordings, the frequency of each sample was accumulated and utilized in displacements calculation. In order to verify the value of displacements, absolute error and maximum error were calculated. The numerical results were indicated that HCBs generate closer displacement with ode45. The error was shown that HCBs could be reliable method and produce accurate displacement of one-mass model of vocal cord.

Keywords:
Hybrid cubic B-spline; Vocal cord displacement; One-mass model

1. Introduction

Speech production is made possible by the vocal cords, which are located in the larynx, or voice box. As air is expelled from the lungs and travels upwards through the trachea, it passes over the vocal cords, causing them to vibrate. This vibration creates sound, which is then modulated by the tongue, lips, and other articulators, allowing human to produce a wide range of speech sounds. The vocal cords play a crucial role in this process, as their ability to rapidly and accurately vibrate determines the quality and clarity of spoken words. The first model of vocal cord is one-mass model of vocal cord by Flanagan and Landgraf in 1968 [1] which then evolved to two-mass model by Ishizaka and Flanagan [2] and Guasch *et al.,* [3]. Two-mass model consider both vocal cord by two equation that represented both measurements. Further years later, Titze produced a model with 16 mass [4,5] and three-mass model was also investigated by other authors in 1993 [6,7]. The wide spread of vocal cord model has increased the study of vocal cord characteristics such as vibrations [8,9], collisions [10,11], self-oscillation [12,13] and aerodynamics [14].

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Numerical method studies began to develop from one-dimensional model [15] to three-dimensional model [16] of mechanical model and commonly solved by using finite element method [17]. These models also heavily aided in the analysis of vocal cord by using numerical and analytical method. Finite element is one of the numerical methods that are usually utilized in solving vocal cord model other than analytical method. Analytical method was less utilized as the method consumed more time than numerical method and sometimes fails to maintain its pace with large or complex value. Some authors that investigated vocal cord model by using finite element were Gunter [18], Vampola *et al.,* [7] and Hermant *et al.,* [19]. Throughout previous years, many works have been done exploring B-spline, trigonometric B-spline and hybrid B-spline for solving initial and boundary value problem of a differential equations numerically [20-24]. Since the ability of those methods have been proven, HCBs will be proposed to solve an initial value problem of one-mass model of vocal cord.

In this work, the 109 recording samples of healthy participant gathered from Walden [25] were used to approximate the displacement of vocal cord. From each sample, the frequencies will be generated by Origin software, which is a software that could analysed the real voices recording. Average of the frequencies has been calculated and applied to solve one-mass model of vocal cord. The aim of this work is to generate displacement of one-mass mechanical model of vocal cord using HCBs and ode45 numerically. Then, the generated displacements will be compared and discussed

1.1 One-Mass Model of Vocal Cord

In this section, one-mass model proposed of vocal cord will be introduced. This model considered vocal cord as a spring-mass-damper system which is visually depict in Figure 1. Mathematically, the model is given by

$$mx'' + bx' + kx = F \tag{1}$$

where *m* is mass, *b* is viscous damping, *k* is spring constant, *F* is forcing function of the system and *x* represent displacement of the mass at time *t*. The value of *b* and *k* are calculated by

$$b = 2\sqrt{mk} \text{ and } k = 4\pi^2 m\left(f_0\right)^2 \tag{2}$$

where f_0 is fundamental frequency. In order to solve Eq. (1), the following initial conditions are considered

$$x\left(t_0\right) = \alpha \text{ and } x'\left(t_0\right) = \beta \tag{3}$$

where α and β are constant values. The forcing function of the system is depending on time and can be written as

$$F\left(t\right) = \frac{1}{2}\left(P_1 + P_2\right)\left(ld\right) \tag{4}$$

with *l* and *d* are the vocal cord length and thickness, respectively. The P_1 and P_2 are the inlet and outlet of glottal orifice of vocal cord which is given by

$$P_1 = \left(P_s - 1.37\ P_B\right) \text{ and } P_2 = -0.50\ P_B \tag{5}$$

where P_s represented subglottal pressure while P_B represent the value of Bernoulli pressure, $P_B = \frac{1}{2}\rho\left|U_g\right|^2 A_g^{-2}$. In Bernoulli pressure equation, ρ represent the air density, A_g is the area of glottal orifice and U_g is the acoustic volume velocity through the glottal orifice.

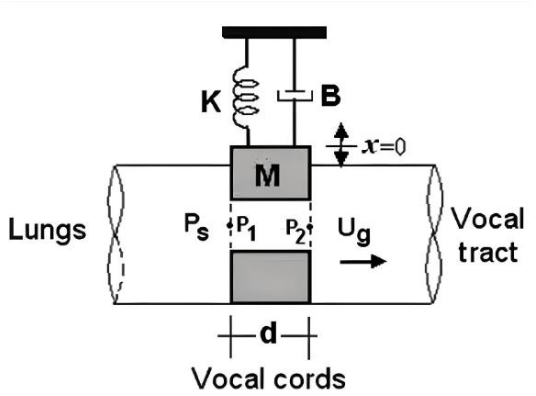

Fig. 1. Mechanical model of vocal cords [1,15]

2. Methodology

2.1 Hybrid Cubic B-Spline Collocation Method (HCBs)

In this section, the methodology to solve Eq. (1) using HCBs is discussed. The approximate solution of one-mass model of vocal cord is defined as

$$x(t_j) = \sum_{j=-3}^{n-1} C_j H_j^4(t) \tag{6}$$

with C_j is unknown to be determined and $H_j^4(t)$ is HCBs basis function which given by

$$H_j^4(t) = \left(\gamma\right) B_j^4(t) + (1-\gamma) T_j^4(t) \tag{7}$$

where $0 < \gamma < 1$. The $B_j^4(t)$ and $T_j^4(t)$ are represented as

$$B_j^4(t) = \frac{1}{6h^3} \begin{cases} (t-t_j)^3, & t \in \left[t_j, t_{j+1}\right] \\ h^3 + 3h^2(t_{j+1}) + 3h^2(t-t_{j+1}) - 3(t-t_{j+1})^3, & t \in \left[t_{j+1}, t_{j+2}\right] \\ h^3 + 3h^2(t_{j+3}-t) + 3h(t_{j+3}-t)^2 - 3(t_{j+3}-t)^3, & t \in \left[t_{j+2}, t_{j+3}\right] \\ (t_{j+4}-t)^3, & t \in \left[t_{j+3}, t_{j+4}\right] \end{cases} \tag{8}$$

and

$$T_j^4(t)=\frac{1}{\theta}\begin{cases}\sigma^3(t_j), & t\in\left[t_j,t_{j+1}\right]\\ (t_j)[\sigma(t_j)\delta(t_{j+2})+\delta(t_{j+3})\sigma(t_{j+1})]+\delta(t_{j+4})\sigma^2(t_{j+1}), & t\in\left[t_{j+1},t_{j+2}\right]\\ \sigma(t_j)\delta(t_{j+3})+\delta(t_{j+4})[\sigma(t_{j+1})\delta(t_{j+3})+\delta(t_{j+3})\sigma(t_{j+2}), & t\in\left[t_{j+2},t_{j+3}\right]\\ \delta^3(t_{j+4}), & t\in\left[t_{j+3},t_{j+4}\right]\end{cases}, \tag{9}$$

respectively, where $\sigma(t_j)=\sin\dfrac{\left(t-t_j\right)}{2}$, $\delta(t_j)=\sin\dfrac{\left(t_j-t\right)}{2}$, and $\theta=\sin\left(\dfrac{h}{2}\right)\sin\left(h\right)\sin\left(\dfrac{3h}{2}\right)$. Eq. (7) become cubic B-spline and trigonometric cubic B-spline when $\gamma=1$ and $\gamma=0$, respectively.

There are only three nonzero basis function; $H_{j-3}^4(t_j)$, $H_{j-2}^4(t_j)$ and $H_{j-1}^4(t_j)$, are included over subinterval $\left[t_j,t_{j+1}\right]$. By considering those nonzero basis functions, Eq. (6) and its derivatives can be simplified and returned as

$$\begin{aligned}x\left(t_j\right)&=D_1C_{j-3}+D_2C_{j-2}+D_1C_{j-1},\\ x'\left(t_j\right)&=D_3C_{j-3}-D_3C_{j-1},\\ x''\left(t_j\right)&=D_4C_{j-3}+D_5C_{j-2}+D_4C_{j-1}\end{aligned} \tag{10}$$

with $D_i=\gamma\eta_i+\left(1-\gamma\right)\varsigma_i$ for $i=1,2,\ldots,5$ where $\eta_1=\dfrac{1}{6}$, $\eta_2=\dfrac{4}{6}$, $\eta_3=\dfrac{1}{2h}$, $\eta_4=\dfrac{1}{h^2}$, $\eta_5=\dfrac{2}{h^2}$, $\varsigma_1=\dfrac{{k_1}^2}{k_2k_3}$, $\varsigma_2=\dfrac{2k_1}{k_3}$, $\varsigma_3=\dfrac{-3}{4k_3}$, $\varsigma_4=\dfrac{3(k_1-2{k_1}^3+k_3)}{8k_1k_2k_3}$, $\varsigma_5=\dfrac{-3(k_4+{k_1}^2k_2)}{4k_1k_2k_3}$, $k_1=\sin\left(\dfrac{h}{2}\right)$, $k_2=\sin\left(h\right)$, $k_3=\sin\left(\dfrac{3h}{2}\right)$ and $k_4=\sin\left(2h\right)$.

In order to solve Eq. (1), Eq. (10) is then substituted into the equation to produce a matrix system of order $\left(n+1\right)$ equation with $\left(n+3\right)$ unknown. Two equations are needed to generate a unique solution. Further, initial condition which given in Eq. (3) is approximated and represented as

$$\begin{aligned}x\left(t_0\right)&=D_1C_{j-3}+D_2C_{j-2}+D_1C_{j-1}=\alpha,\\ x'\left(t_0\right)&=D_3C_{j-3}-D_3C_{j-1}=\beta.\end{aligned} \tag{11}$$

Eq. (11) is added to the system and become

$$\left[\mathbf{A}\right]_{(n+3)\times(n+3)}.\left[\mathbf{C}\right]_{(n+3)\times 1}=\left[\mathbf{R}\right]_{1\times(n+3)} \tag{12}$$

where $\mathbf{A}=\begin{bmatrix} D_1 & D_2 & D_1 & 0 & \cdots & \cdots & \cdots & 0 \\ \omega_1 & \omega_2 & \omega_3 & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & \omega_1 & \omega_2 & \omega_3 & 0 & \cdots & \cdots & 0 \\ \vdots & 0 & \omega_1 & \omega_2 & \omega_3 & 0 & \cdots & 0 \\ 0 & \cdots & \ddots & \ddots & \ddots & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots & \cdots & 0 & \omega_1 & \omega_2 & \omega_3 \\ D_3 & 0 & D_3 & 0 & \cdots & \cdots & \cdots & 0 \end{bmatrix}$, $\mathbf{C}=\begin{bmatrix} C_{-3} \\ C_{-2} \\ C_{-1} \\ \\ \vdots \\ \\ C_{n-1} \end{bmatrix}$ and $\mathbf{F}=\begin{bmatrix} \alpha \\ F \\ \vdots \\ \\ \vdots \\ F \\ \beta \end{bmatrix}$ with $\omega_1 = m(D_4)+b(D_3)+k(D_1)$, $\omega_2 = m(D_5)+k(D_2)$ and $\omega_3 = m(D_4)+b(-D_3)+k(D_1)$. By solving the matrix system, $\mathbf{C}$ is generated and substituted into Eq. (6) to obtain the approximate solution of Eq. (1) or also known as approximate displacement of vocal cord.

2.2 Ode45 Built-in Solver

By using the same parameter as HCBS, Eq. (1) is also solved by using a build-in solver in MATLAB called ode45 as follows:

```
f = @(t,x) [x(2); (F-r*x(2)-k*x(1))/m];
tspan=t0:(0.05-0)/(n):tN;
ts = zeros(1,n); xs = zeros(1,n);
[ts,xs] = ode45(f,tspan,[0;0]);
```

3. Results and Discussion

In this section, the generated displacements of vocal cord by using HCBs and ode45 are analysed and compared. Two values of γ for HCBs are considered as $\gamma = 0.30$ and $\gamma = 0.99$. The parameters used are shown in Table 1. The frequency value, f_0, is chosen from the average frequency of voice recording samples. Otherwise, the parameters are mostly referred from Flanagan and Landgraf [1] and Cataldo *et al.,* [15].

Table 1
Parameters value used in solving Eq. (1)

Parameter	Value
m	0.240×10^{-3} kg
b	0.667 Ns/m
k	4.925×10^{5} Ns/m
t	0.050 s
P_{s0}	783 Pa
ρ	1.300×10^{3} kg/m^3
l	1.800×10^{-2} m
d	0.300×10^{-3} m
f_0	228 Hz
h	1.000×10^{-4}

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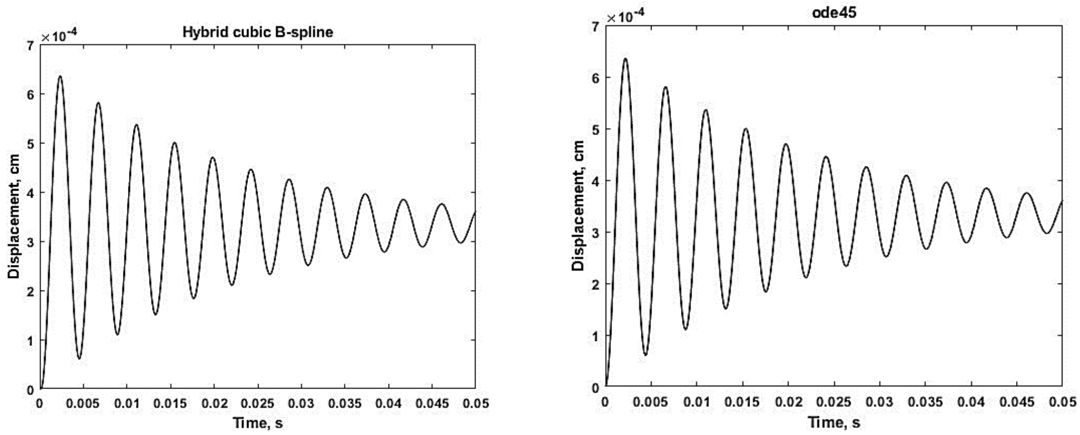
3.1 HCBs $(\gamma = 0.30)$ and Ode45

In this subsection, the generated displacement by HCBs ($\gamma = 0.30$) and ode45 is displayed and tabulated. Figure 2 shows graph of generated displacement by HCBs ($\gamma = 0.30$) and ode45.



(a) (b)

Fig. 2. Generated displacements by a) HCBs with $\gamma = 0.30$ and b) ode45

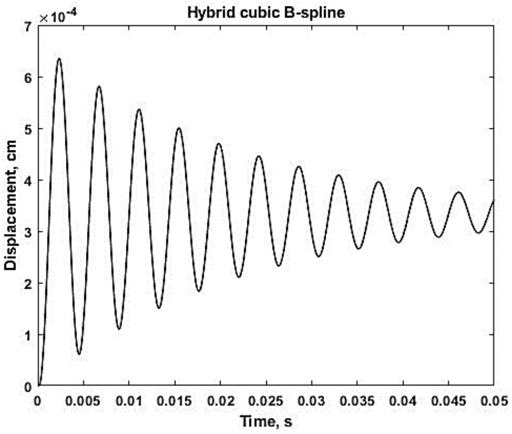
Meanwhile, the numerical data of both method within 0.05 s is listed and compared in Table 2. The data shows that the generated displacement by HCBs agreed well with the generated displacement by ode45.

Table 2
Generated displacement solved by ode45 (x -ode45) and HCBs (x -hybrid) with $\gamma = 0.30$ within 0.050 s

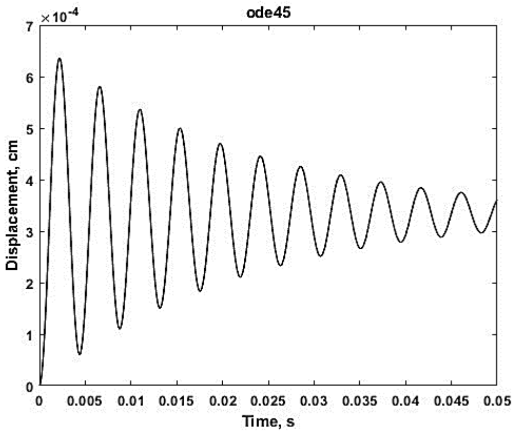
Time (s)	x -ode45 (cm)	x -hybrid (cm)
0.010	3.5399×10^{-4}	3.6302×10^{-4}
0.015	4.7113×10^{-4}	4.7732×10^{-4}
0.020	4.6581×10^{-4}	4.6291×10^{-4}
0.025	3.8562×10^{-4}	3.7531×10^{-4}
0.030	3.0445×10^{-4}	3.9434×10^{-4}
0.035	2.6992×10^{-4}	2.6679×10^{-4}
0.040	2.8515×10^{-4}	2.8999×10^{-4}
0.045	3.2317×10^{-4}	3.3141×10^{-4}
0.050	3.5357×10^{-4}	3.5926×10^{-4}

3.2 HCBs $(\gamma = 0.99)$ and Ode45

The generated displacement by HCBs with $\gamma = 0.99$ and ode45 are presented in Figure 3.



(a)



(b)

Fig. 3. Generated displacements by a) HCBs with $\gamma = 0.99$ and b) ode45

Table 3 tabulates the generated displacement of both method within 0.050 s. Based on the results, it can be seen that the HCBs of $\gamma = 0.99$ could also performed well compared to HCBs of $\gamma = 0.30$.

Table 3
Generated displacement solved by ode45 (x -ode45) and HCBs (x -hybrid) with $\gamma = 0.99$ within 0.050 s

Time (s)	x-ode45 (cm)	x -hybrid (cm)
0.010	3.5399×10^{-4}	3.6302×10^{-4}
0.015	4.7113×10^{-4}	4.7732×10^{-4}
0.020	4.6581×10^{-4}	4.6291×10^{-4}
0.025	3.8562×10^{-4}	3.7531×10^{-4}
0.030	3.0445×10^{-4}	2.9433×10^{-4}
0.035	2.6992×10^{-4}	2.6679×10^{-4}
0.040	2.8515×10^{-4}	2.8999×10^{-4}
0.045	3.2317×10^{-4}	3.3141×10^{-4}
0.050	3.5357×10^{-4}	3.5929×10^{-4}

In order to compare the displacements of HCBs of $\gamma = 0.30$ and $\gamma = 0.99$, the maximum displacement from Table 2 and Table 3 are gathered in Table 4. It can be observed that maximum displacement is at $t = 0.015\ s$ which is presented in Table 4. The obtained displacements in Table 4 also shows that $\gamma = 0.99$ has slightly lower maximum displacement than $\gamma = 0.30$. Since ode45 has the maximum displacement of 4.7113×10^{-4} cm, this interprets that $\gamma = 0.99$ has closer value of maximum displacement to ode45 than $\gamma = 0.30$.

Table 4
Maximum displacement (x -max) generated by HCBs with $\gamma = 0.30$ and $\gamma = 0.99$

γ	Time (s)	x -max (cm)
0.30	0.015	4.77324816×10^{-4}
0.99	0.015	4.77324815×10^{-4}

3.3 Absolute Error Obtained by HCBs Compared to Ode45

This subsection calculates the absolute error and maximum error by comparing the generated displacement by HCBs and ode45. The formula is considered as the following equations:

$$Absolute\ error = \left|\overline{x}_i - x_i\right|, \tag{13}$$

$$Maximum\ error = L_\infty = max\left|\overline{x}_i - x_i\right|, \tag{14}$$

where $\overline{x}_i$ is generated displacements by ode45 and x_i generated displacements by HCBs.

Table 5 list the absolute errors within 0.050 s. Meanwhile the maximum error obtained by HCBs with $\gamma = 0.30$ and $\gamma = 0.99$ is tabulated in Table 6. Based on Table 5, it can be seen that $\gamma = 0.99$ obtained smaller error than $\gamma = 0.30$.

Table 5
Absolute errors obtained by HCBs with $\gamma = 0.30$ and $\gamma = 0.99$ within 0.050 s

Time (s)	Absolute error	
	$\gamma = 0.30$	$\gamma = 0.99$
0.010	9.0351910×10^{-6}	9.0351889×10^{-6}
0.015	6.1986152×10^{-6}	6.1986139×10^{-6}
0.020	2.8956127×10^{-6}	2.8956117×10^{-6}
0.025	1.0312675×10^{-5}	1.0312673×10^{-5}
0.030	1.0117635×10^{-5}	1.0117632×10^{-5}
0.035	3.1378975×10^{-6}	3.1378972×10^{-6}
0.040	4.8454254×10^{-6}	4.8454240×10^{-6}
0.045	8.2377835×10^{-6}	8.2377816×10^{-6}
0.050	5.6899366×10^{-6}	5.6899355×10^{-6}

From Table 6, it can be observed that $\gamma = 0.99$ has obtained smaller maximum error than $\gamma = 0.30$. Overall, the numerical data of Table 5 and 6 suggest that $\gamma = 0.99$ generate closer displacement to ode45 in solving one-mass model of vocal cord than $\gamma = 0.30$.

Table 6
Maximum error obtained by HCBs with $\gamma = 0.30$ and $\gamma = 0.99$

γ	Time (s)	Maximum error
0.30	0.025	1.0312675×10^{-5}
0.99	0.025	1.0312673×10^{-5}

4. Conclusions

In conclusion, one-mass model of vocal cord has successfully solved by using HCBs collocation method. The numerical results indicate that HCBs has generated displacement with closer value to ode45. The calculated errors shown that HCBs produce accurate displacement of vocal cord could be reliable numerical method in solving one-mass model of vocal cord.

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