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On the wave propagations of football game ball after contacting with the player foot

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Abstract. Wave propagation with high transverse deflection could affect the stability of the ball in its trajectory. For low stiffness balls similar to soccer and volleyball balls, the waves are more noticeable in comparison to other balls like ping-pong ball. On the other hand, the soccer balls are under heavy impact loads from shoots and contacting different objects in the field. The maximum recorded speed of a soccer ball after kicking is the 211 km/hr and the average maximum speed is around 112 km/hr. Therefore, in such speeds the aerodynamic forces become important which are directly related to geometrical shape of the ball. In this regard, the wave propagation in soccer ball is examined in the current study using large deformation shear deformable formulations. Classical relations of stress-strain components are taken into consideration along with minimum total energy principle. The final derived relations were solved by using harmonic differential quadrature method. The results are generally presented ion term of phase velocity as function of different influencing parameters of the materials, geometry and mass of the ball.

Keywords: analytical analysis; contact; football game ball; vibration; wave propagation

1. Introduction

Wave propagation in different solid structures have the focus of several research areas. In the seismic studies, accurate prediction of wave propagation, its velocity and amplitude could help civil engineers to design and predict the vibration state in different locations(Dai *et al.* 2023, Peng *et al.* 2023, Sabzevari *et al.* 2023, Yang *et al.* 2023, Zhao *et al.* 2023, Zheng *et al.* 2023). In the non-destructive tests, the wave propagation in solids and its confrontation with new surfaces are very important to detect a fault are in the solid materials (Zhang *et al.* 2014, Ebrahimi and Barati 2017, De Domenico *et al.* 2019, Al-Furjan *et al.* 2020n, Al-Furjan *et al.* 2020x, Li *et al.* 2020a). In addition, in the medical area, the wave propagation in the internal organs are different and should be treated differently in the imaging processes(Habibi *et al.* 2016, Habibi *et al.* 2018a, Habibi *et al.* 2018b, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019, Habibi *et al.* 2019b, Habibi *et al.* 2019d, Habibi *et al.* 2019e, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a, Zhu *et al.* 2022b, Dai *et al.* 2023, Zheng *et al.* 2023). In the case of sport balls, wave propagation with high transverse deflection could affect the stability of the ball in its trajectory.

A schematic view of football game ball after contacting with the player foot can be seen in Fig. 1. For low stiffness balls similar to soccer and volleyball balls, the waves are more noticeable in comparison to other balls like ping-pong ball. On the other hand, the soccer balls are under heavy impact loads from shoots and contacting different objects in the field. The maximum recorded speed of a soccer ball after kicking is the 211 km/hr and the average maximum speed is around 112 km/hr. Therefore, in such speeds the aerodynamic forces become important which are directly related to geometrical shape of the ball. The constant changes in the ball shape due to wave propagation could affect the value and direction of the aerodynamic forces. Therefore, understanding the state of wave propagation, its shape, its amplitude and pattern could aid designers and manufacturers of such product to improve the materials for better performance of the balls. Wave propagation in sport balls could be modeled using elasticity formulation in structural mechanics via shell displacement field relations. However, small-deformation formulations could not adequately reflect the behavior of oscillation in the ball. Therefore, nonlinear formulations are required for understanding the wave propagation in large deformation space (Arabnejad Khanouki *et al.* 2010, Shariati *et al.* 2012, Shah *et al.* 2015, Ismail *et al.* 2018, Wei *et al.* 2018, Sajedi and Shariati 2019, Shariati *et al.* 2019a, Naghipour *et al.* 2020a, Naghipour *et al.* 2020b, Shariat *et al.* 2020, Shariati *et al.* 2020a, Shariati *et al.* 2020b, Shariati *et al.* 2020g, Shariati *et al.* 2020h, Shariati *et al.* 2020j, Shariati *et al.* 2020k, Toghroli *et al.* 2020, Shariati *et al.* 2021a, Shariati *et al.* 2022a, Shariati *et al.* 2022b, Tavakkoli *et al.* 2022a). The

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Fig. 1 A schematic of football game ball after contacting with the player foot

wave propagation relations are in close connection with vibration relations. Spherical shell models with different material patterns have been investigated enormously in the literature. Shen and Fan (2023) investigated the state of wave propagation in volleyball ball under the effect of dynamic impact loading occurs during hitting the ground. Both numerical differential quadrature and finite elements methods were engaged for obtaining the effects of total mass, material properties and radius of the shell model on the wave propagation and stability of the ball. Al-Furjan *et al.* (2020w) investigated the condition of wave propagation in cylindrical shell structure under the spinning condition. They utilized four different elasticity theory to understand the effects of small size effects and on the phase velocity of the composite cylindrical shell. Karami and Shahsavari (Karami and Shahsavari 2020) examined the vibration in spherical shell model made of composite materials. They considered third-order shear deformation theory for the displacement field and two different curvature radius in different direction for the geometry of the shell. In addition, functionally grading properties were also included in the analyses. They found, through numerical solution of the governing equations, that geometrical and grading properties of the shell structure had the most important effects on the vibration characteristics of the shell structure. Ghavanloo *et al.* (2019) utilized a novel approach for nonlocal elasticity formulation of spherical shell to observe the vibrational responses in nano-scale fullerene structures. Spherical shell structures could be regarded as doubly-curved shells. Cao *et al.* (2021) considered grading material properties in three different direction to examine free oscillation responses in spherical nano-composite member. The governing equations were obtained using Hamilton's principle and solved by Galerkin's method.

The instability of shell structures have also received extensive attentions in the literature (Sudak 2003, Vodenitcharova and Zhang 2006, Pradhan and Reddy 2011, Ansari *et al.* 2015, Nejad *et al.* 2016, Issad *et al.* 2018, Ahmed *et al.* 2019, Thai *et al.* 2019, Rémond *et al.* 2022).

Barretta *et al.* (2020) evaluated buckling loading beam structures using nonlocal elasticity theory. State of boundary constraints are extracted using nonlocal formulation. The dependency of critical axial loading on vaious paramters are examined and compared to the respective results obtained by strain gradient theory. Rémond *et al.* (2022) explored the buckling condition of ping-pong balls under dynamic loading. They found that there is marginal differences between dynamic and quasi-static buckling criteria in terms of required deflection for initiation of buckling. In addition, the energy loss during impact condition is mostly due to friction between ball and the surface. Esmailpoor Hajilak *et al.* (2019) utilized modified strain gradient theory to identify the buckling and vibration responses of cylindrical shell structures under thermal loadings. They reported the dependency of buckling load, vibration frequency and deflection on different parameters pertaining to material and constitutive theory. Sahmani and Aghdam (2017) reported the post-buckling behavior in radial direction for layer-wise shell structure.

They utilized shear deformation based theories and nonlocal strain gradient theories. They considered several configurations for distribution of nano-fillers in the composite and reported the buckling behavior of the structure. There could be found other data on the spherical shell structures (Ghavanloo *et al.* 2019, Van Do and Lee 2020). As discussed above, the wave propagation in soccer ball under impact loading condition has not been examined theoretically using shell formulations. In this regard, the wave propagation in soccer ball is examined in the current study using large deformation shear deformable formulations. Classical relations of stress-strain components are taken into consideration along with minimum total energy principle. The final derived relations were solved by using harmonic differential quadrature method. The results are generally presented ion term of phase velocity as function of different influencing parameters of the materials, geometry and mass of the ball.

2. Mathematical formulation of ball

The displacement field of the spherical shell is expressed by (Fazaeli *et al.* 2016, Habibi *et al.* 2017, Safarpour *et al.* 2018, Habibi *et al.* 2019a, Habibi *et al.* 2019c, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Ghazanfari *et al.* 2020, Safarpour *et al.* 2020, Chen *et al.* 2022)

$$u(\phi,\theta,z,t) = u_0(\phi,\theta,t) + \mathrm{f}_1(z)u_1(\phi,\theta,t) + \mathrm{f}_2(z)u_2(\phi,\theta,t) \tag{1}$$

$$v(\phi,\theta,z,t) = v_0(\phi,\theta,t) + \mathrm{f}_1(z)v_1(\phi,\theta,t) + \mathrm{f}_2(z)v_2(\phi,\theta,t) \tag{2}$$

$$w(\phi,\theta,z,t) = w_0(\phi,\theta,t) \tag{3}$$

where u_0, v_0, w_0, u_1, u_2, v_1, v_2, and w_0 are the unknown displacement functions.

In which $f_1(z)$ and $f_2(z)$ are given by Nguyen (Nguyen *et al.* [41]) as follows

$$f_1(z) = \frac{5}{4}z - \frac{5z^3}{3h^2}; f_2(z) = \frac{5z^3}{3h^2} - \frac{1}{4}z \tag{4}$$

Where strain displacement can be defined as follows (Ebrahimi *et al.* 2019b, Ebrahimi *et al.* 2019c, Hashemi *et* *al.* 2019, Moayedi *et al.* 2019, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Ebrahimi *et al.* 2020b, Habibi *et al.* 2020, Moayedi *et al.* 2020a, Moayedi *et al.* 2020b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020c, Shariati *et al.* 2020d, Shokrgozar *et al.* 2020)

$$\varepsilon_{\phi\phi}=\frac{\partial u}{r\,\partial\phi}+\frac{w}{r},\quad \varepsilon_{\theta\theta}=\frac{\partial v}{r_1\,\partial\theta}+\frac{u}{rr_1}\frac{\partial R_1}{\partial\phi}+\frac{w}{r},\quad \varepsilon_{ZZ}=\frac{\partial w}{\partial Z} \tag{5}$$

$$\gamma_{\phi\theta}=\frac{\partial v}{r\,\partial\phi}-\frac{v}{rr_1}\frac{\partial R_1}{\partial\phi}+\frac{\partial u}{r_1\,\partial\theta},\quad \gamma_{\phi Z}=\frac{\partial u}{\partial Z}-\frac{u}{r}+\frac{\partial w}{r\,\partial\phi},\quad \gamma_{\theta Z}=\frac{\partial v}{\partial Z}-\frac{v}{r}+\frac{\partial w}{r_1\,\partial\theta} \tag{6}$$

By substituting $r_1=r\sin\emptyset$ in Eqs. (5), and (6)

$$\varepsilon_{\phi\phi}=\frac{\partial u}{r\,\partial\phi}+\frac{w}{r},\quad \varepsilon_{\theta\theta}=\frac{1}{r\sin(\phi)}\frac{\partial v}{\partial\theta}+\frac{\cot(\phi)u}{r}+\frac{w}{r},\quad \varepsilon_{ZZ}=\frac{\partial w}{\partial Z} \tag{7}$$

$$\varepsilon_{\phi\theta}=\frac{\partial v}{r\,\partial\phi}-\frac{\cot(\phi)v}{r}+\frac{1}{r\sin(\phi)}\frac{\partial u}{\partial\theta},\quad \varepsilon_{\phi Z}=\frac{\partial u}{\partial Z}-\frac{u}{r}+\frac{\partial w}{r\,\partial\phi},\quad \varepsilon_{\theta z}=\frac{\partial v}{\partial Z}-\frac{v}{r}+\frac{1}{r\sin(\phi)}\frac{\partial w}{\partial\theta} \tag{8}$$

Where (She *et al.* 2022, Zhang *et al*. 2022a, Cheng *et al.* 2023)

$$\varepsilon_{\phi\phi}=\varepsilon_{\phi\phi}^{(0)}+f_1(z)\varepsilon_{\phi\phi}^{(1)}+f_2(z)\varepsilon_{\phi\phi}^{(2)} \tag{9}$$

$$\varepsilon_{\theta\theta}=\varepsilon_{\theta\theta}^{(0)}+f_1(z)\varepsilon_{\theta\theta}^{(1)}+f_2(z)\varepsilon_{\theta\theta}^{(2)} \tag{10}$$

$$\varepsilon_{zz}=0 \tag{11}$$

$$\varepsilon_{\phi z}=\varepsilon_{\phi z}^{(0)}+f_1(z)\varepsilon_{\phi z}^{(1)}+f_2(z)\varepsilon_{\phi z}^{(2)}+\frac{\partial f_1(z)}{\partial z}\varepsilon_{\phi z}^{(3)}+\frac{\partial f_2(z)}{\partial z}\varepsilon_{\phi z}^{(4)} \tag{12}$$

$$\varepsilon_{\theta z}=\varepsilon_{\theta z}^{(0)}+f_1(z)\varepsilon_{\theta z}^{(1)}+f_2(z)\varepsilon_{\theta z}^{(2)}+\frac{\partial f_1(z)}{\partial z}\varepsilon_{\theta z}^{(3)}+\frac{\partial f_2(z)}{\partial z}\varepsilon_{\theta z}^{(4)} \tag{13}$$

$$\varepsilon_{\phi\theta}=\varepsilon_{\phi\theta}^{(0)}+f_1(z)\varepsilon_{\phi\theta}^{(1)}+f_2(z)\varepsilon_{\phi\theta}^{(2)} \tag{14}$$

where (Wang *et al.* 2022a, Zhu *et al.* 2022a, Liu *et al.* 2023)

$$\varepsilon_{\phi\phi}^{(0)}=\frac{1}{r}\frac{\partial u_0}{\partial\emptyset}+\frac{w_0}{r},\ \varepsilon_{\phi\phi}^{(1)}=\frac{1}{r}\frac{\partial u_1}{\partial\emptyset},\ \varepsilon_{\phi\phi}^{(2)}=\frac{1}{r}\frac{\partial u_2}{\partial\emptyset} \tag{15}$$

$$\varepsilon_{\theta\theta}^{(0)}=\frac{1}{r\sin(\emptyset)}\frac{\partial v_0}{\partial\theta}+\frac{\cot(\emptyset)}{r}u_0+\frac{w_0}{r},\ \varepsilon_{\theta\theta}^{(1)}=\frac{1}{r\sin(\emptyset)}\frac{\partial v_1}{\partial\theta}+\frac{\cot(\emptyset)}{r}u_1 \tag{16}$$

$$\varepsilon_{\theta\theta}^{(2)}=\frac{1}{r\sin(\emptyset)}\frac{\partial v_2}{\partial\theta}+\frac{\cot(\emptyset)}{r}u_2,\ \varepsilon_{\phi z}^{(0)}=-\frac{u_0}{r}+\frac{1}{r}\frac{\partial w_0}{\partial\emptyset},\ \varepsilon_{\phi z}^{(1)}=-\frac{u_1}{r},\ \varepsilon_{\phi z}^{(2)}=-\frac{u_2}{r} \tag{17}$$

$$\varepsilon_{\phi z}^{(3)}=u_1,\ \varepsilon_{\phi z}^{(4)}=u_2,\ \varepsilon_{\theta z}^{(0)}=-\frac{v_0}{r}+\frac{1}{r\sin(\emptyset)}\frac{\partial w_0}{\partial\emptyset},\ \varepsilon_{\theta z}^{(1)}=-\frac{v_1}{r},\ \varepsilon_{\theta z}^{(2)}=-\frac{v_2}{r} \tag{18}$$

$$\varepsilon_{\theta z}^{(3)}=v_1,\ \varepsilon_{\theta z}^{(4)}=v_2,\ \varepsilon_{\phi\theta}^{(0)}=\frac{1}{r}\frac{\partial v_0}{\partial\emptyset}-\frac{\cot(\emptyset)}{r}v_0+\frac{1}{r\sin(\emptyset)}\frac{\partial u_0}{\partial\theta} \tag{19}$$

$$\varepsilon_{\phi\theta}^{(1)}=\frac{1}{r}\frac{\partial v_1}{\partial\emptyset}-\frac{\cot(\emptyset)}{r}v_1+\frac{1}{r\sin(\emptyset)}\frac{\partial u_1}{\partial\theta},\ \varepsilon_{\phi\theta}^{(2)}=\frac{1}{r}\frac{\partial v_2}{\partial\emptyset}-\frac{\cot(\emptyset)}{r}v_2+\frac{1}{r\sin(\emptyset)}\frac{\partial u_2}{\partial\theta} \tag{20}$$

For the elastic system we have(Hashemi *et al.* 2019, Al-Furjan *et al*. 2020e, Al-Furjan *et al.* 2020o, Al-Furjan *et al.* 2020q, Al-Furjan *et al.* 2020s, Bai *et al.* 2020, Cheshmeh *et al.* 2020, Li *et al.* 2020b, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020e, Xiong *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a)

$$\sigma_{\emptyset\emptyset}=(Q_{11}\varepsilon_{\emptyset\emptyset}+Q_{12}\varepsilon_{\theta\theta}) \tag{21}$$

$$\sigma_{\theta\theta}=(Q_{12}\varepsilon_{\emptyset\emptyset}+Q_{22}\varepsilon_{\theta\theta}) \tag{22}$$

$$\tau_{\theta z}=(Q_{44}\varepsilon_{\theta z}) \tag{23}$$

$$\tau_{\emptyset z}=(Q_{55}\varepsilon_{\emptyset z}) \tag{24}$$

$$\tau_{\emptyset\theta}=(Q_{66}\varepsilon_{\emptyset\theta}) \tag{25}$$

where(Adamian *et al.* 2020, Al-Furjan *et al.* 2020c, Al-Furjan *et al.* 2020d, Li *et al.* 2020c, Liu *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021b, Zhang *et al.* 2021)

$$Q_{11}=\frac{E}{(1-\nu^2)},\ Q_{22}=Q_{11} \tag{26}$$

$$Q_{12}=\frac{\nu E}{(1-\nu^2)},\quad Q_{21}=Q_{12} \tag{27}$$

$$Q_{44}=\frac{E}{2(1+\nu)},\quad Q_{66}=Q_{55}=Q_{44} \tag{28}$$

The equations that determine motion are derived based on Hamilton's principle (Liu *et al.* 2020a, Wang *et al.* 2020, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021a, Shao *et al.* 2021, Wu and Habibi 2021, Kong *et al.* 2022)

$$\delta\int_{t_1}^{t_2}\big(\Pi_k-(\Pi_e+\Pi_w)\big)dt=0 \tag{29}$$

Where Π_k, Π_e, and Π_w stand for the kinetic energy, potential energy, and work done by the system respectively (Hou *et al.* 2021, Liu et al. 2021c, Luo *et al.* 2022b, Moradi *et al.* 2022, Wang *et al.* 2022b, Wang *et al.* 2022c, Yang *et al.* 2022a, Fang *et al.* 2023, Jin *et al.* 2023, Wang *et al.* 2023).

The kinetic energy of the moving plate is indicated as follows (Lu *et al.* 2022, Qin *et al.* 2022)

$$\Pi_k = \int_V \frac{1}{2}\rho(\phi,\theta,z)\left[\left(\frac{\partial u}{\partial t}\right)^2 + \left(\frac{\partial V}{\partial t}\right)^2 + \left(\frac{\partial w}{\partial t}\right)^2\right] dV \quad (30)$$

The potential energy of the axially moving plate is illustrated as follows (Davoodnabi *et al.* 2021, Hosseini and Toghroli 2021, Nouri *et al.* 2021, Shariati *et al.* 2021a, Shariati *et al.* 2021b, Hosur Shivaramaiah *et al.* 2022, Naveen Kumar *et al.* 2022, Shariati *et al.* 2022a, Shariati *et al.* 2022b, Tavakkoli *et al.* 2022b)

$$\Pi_u = \int_V \frac{1}{2}\left[\sigma_{\phi\phi}\varepsilon_{\phi\phi} + \sigma_{\theta\theta}\varepsilon_{\theta\theta} + \tau_{\theta z}\gamma_{\theta z} + \tau_{\phi z}\gamma_{\phi z} + \tau_{\phi\theta}\gamma_{\phi\theta}\right] dV \quad (31)$$

The work done by the system (Dong *et al.* 2022, Fan et *al.* 2022a, Fan *et al.* 2022b, Hu *et al.* 2022, Huang *et al.* 2022, Luo *et al.* 2022a, Yang *et al.* 2022b, Zhang *et al.* 2022b, Zheng *et al.* 2022, Zhou *et al.* 2022a)

$$\Pi_u = \int_A \frac{\mathcal{P}}{2}\left\{\left(\frac{1}{r^2\sin(\phi)}\frac{\partial}{\partial\phi}\left(\sin(\phi)\frac{\partial w_0}{\partial\phi}\right)\right) + \frac{1}{r^2\sin^2(\phi)}\frac{\partial^2 w_0}{\partial\theta^2}\right\} w_0 dA \quad (32)$$

Where P indicates the In-plane mechanical loading (Huang *et al.* 2021b, Jiao *et al.* 2021, Ma *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021; Zhao *et al.* 2021, Michael et al. 2022, Yu *et al.* 2022, Zhou *et al.* 2022b). Substituting Eqs. (30)-(32) into Eq. (29), the governing equations of motion can be obtained.

3. Solution procedure

In order to demonstrate the associated approximations in harmonic differential quadrature method (HDQM) through one-dimensional function (Al-Furjan *et al.* 2020a, Al-Furjan *et al.* 2020b, Al-Furjan *et al.* 2020g, Al-Furjan *et al.* 2020f, Al-Furjan *et al.* 2020h, Al-Furjan *et al.* 2020i, Al-Furjan *et al.* 2020j, Al-Furjan *et al.* 2020k, Al-Furjan *et al.* 2020l, Al-Furjan *et al.* 2020m, Al-Furjan *et al.* 2020n, Al-Furjan *et al.* 2020p, Al-Furjan *et al.* 2020r, Al-Furjan *et al.* 2020t, Al-Furjan *et al.* 2020u, Al-Furjan *et al.* 2020v, Al-Furjan *et al.* 2021a, Al-Furjan *et al.* 2021b), the following relation declares the p^{th} derivative of $\mathcal{F}(\phi)$ as the function of $\emptyset$ as below

$$\frac{\partial^p\mathcal{F}(\phi)}{\partial\phi^p} = \sum_{j=1}^{N}\mathcal{G}_{ij}^{(p)}\mathcal{F}(\phi) \qquad \mathcal{F}or\ i = 1,2,\ldots,N_\emptyset \ and\ p = 1,2,\ldots,N_\emptyset - 1 \quad (33)$$

here $N_\emptyset$ indicates the total number of discrete grid nodes selected through the solution domain. The term $\mathcal{G}_{ij}^{(p)}$ shows the weight coefficients $(j = 1,2,\ldots,N_\emptyset)$ at the ith grid-point located in the solution domain. The weight coefficients related to the first-order derivatives $\mathcal{G}_{ij}^{(1)}$ for $i \neq j$ would be determined through the following relation

$$\mathcal{G}_{\text{ij}}^{(1)} = \frac{\pi \text{P}(\emptyset_i)}{2\text{P}(\emptyset_j)\sin\left[(\emptyset_i\text{-}\emptyset_j)/2\pi\right]}, \text{i,j=1,2,...,N}_\emptyset \quad (34)$$

here

$$P(\emptyset_i)\text{=-}\sum_{\text{j=1,j}\neq i}^{N_\emptyset}\sin\left(\frac{\pi(\emptyset_i\text{-}\emptyset_j)}{2}\right), \text{for j=1,2,3,...,N}_\emptyset \quad (35)$$

The weight coefficients related to the first-order derivatives $\mathcal{G}_{ij}^{(1)}$ when $i = j$ can be acquired as below

$$\mathcal{G}_{\text{ii}}^{(1)}\text{=-}\sum_{\text{j=1,j}\neq i}^{N_\emptyset}\mathcal{G}_{\text{ij}}^{(1)}, \text{for i=1,2,3,...,N}_\emptyset \quad (36)$$

The weight coefficients related to the second-order derivatives $\mathcal{G}_{ij}^{(2)}$ when $i \neq j$ would be acquired through the subsequent relation (Zainah and Shahaboddin 1801, Khanouki *et al.* 2016, Shah *et al.* 2016a, Shah *et al.* 2016b, Shariati *et al.* 2016, Tahmasbi *et al.* 2016, Khorami *et al.* 2017, Shariati *et al.* 2018, Milovančević *et al.* 2019, Shariati *et al.* 2019b, Shariati *et al.* 2019c, Suhatril *et al.* 2019, Razavian *et al.* 2020, Shariati *et al.* 2020f, Shariati *et al.* 2020i, Shariati *et al.* 2021c, Shariati *et al.* 2021d, Shariati *et al.* 2021e, Shariati *et al.* 2021f, Yazdani *et al.* 2021, Jahandari *et al.* 2022; Tavakkoli *et al.* 2022a)

$$\mathcal{G}_{\text{ij}}^{(2)}\text{=}\mathcal{G}_{\text{ij}}^{(1)}\left(2\mathcal{G}_{\text{ij}}^{(1)}\text{-}\pi\cot\left(\frac{\emptyset_i\text{-}\emptyset_j}{2}\times\pi\right)\right), \text{i,j=1,2,3,...,N}_\emptyset \quad (37)$$

The weight coefficients related to the second-order derivatives $\mathcal{G}_{ij}^{(2)}$ when $i = j$ would be determined as

$$\mathcal{G}_{\text{ii}}^{(2)}\text{=-}\sum_{\text{j=1,j}\neq i}^{N_r}\mathcal{G}_{\text{ij}}^{(2)}, \text{for i=1,2,3,...,N}_\emptyset \quad (38)$$

Also, the Chebyshev–Gauss–Lobatto grid distribution is chosen. In this distribution, the co-ordinates of grid points $(\emptyset_i)$ are calculated by the flowing equation across the reference surface

$$\phi_i = \phi_0 + \frac{\phi}{2}\left(1 - \cos\left(\frac{(i-1)}{(N_\phi - 1)}\pi\right)\right) \qquad i = 1,2,3,\ldots,N_\phi \quad (39)$$

The displacement field expressions are given as below

$$u_0(\phi,\theta,t) = U_0(\phi)exp(k\theta i - \omega t i), \qquad V_0(\phi,\theta,t) = V_0(\phi)exp(k\theta i - \omega t i) \quad (40)$$

$$w_0(\phi,\theta,t) = W_0(\phi)exp(k\theta i - \omega ti),$$
$$u_1(\phi,\theta,t) = U_1(\phi)exp(k\theta i - \omega ti) \tag{41}$$

$$V_1(\phi,\theta,t) = V_1(\phi)exp(k\theta i - \omega ti),$$
$$u_2(\phi,\theta,t) = U_2(\phi)exp(k\theta i - \omega ti) \tag{42}$$

$$V_2(\phi,\theta,t) = V_2(\phi)exp(k\theta i - \omega ti) \tag{43}$$

Substitution of Eqs. (40)-(43) into governing equations have

$$\left\{\begin{bmatrix}[\mathcal{M}_{dd}] & [\mathcal{M}_{db}]\\ [\mathcal{M}_{bd}] & [\mathcal{M}_{bb}]\end{bmatrix}\omega^2 + \begin{bmatrix}[\mathcal{K}_{dd}] & [\mathcal{K}_{db}]\\ [\mathcal{K}_{bd}] & [\mathcal{K}_{bb}]\end{bmatrix}\right\}\begin{Bmatrix}\Xi_d\\ \Xi_b\end{Bmatrix} = 0 \tag{44}$$

Also, the phase velocity can be calculated by Eq. (45)

$$phase\ velocity(J) = \frac{\omega}{k} \tag{45}$$

4. Numerical results and discussion

4.1 Material constants

The mass and span angle of the ball model are presented in Table 1 as adopted from Ref. (Zhang *et al.* 2020).

4.2 Validation

Results of the above presented methodologies are presented n Table 2 for the purpose of comparison with another method presented in Ref. (Qu 2013). As could be noticed in this table, the current methodology provides accurate free oscillation frequency results for different conditions of boundaries and wave numbers as compared to the selected references. It is also seen that increase in the k parameter results in increase in the natural frequency of the structure.

Table 1 The material properties associated with ball

$m_b\ (gr) = 260$
$\emptyset_{\mathrm{i}} = 10\ [deg]$
$\emptyset_o = 170\ [deg]$

Table 2 Comparison of natural frequencies $f = \omega/2\pi$(Hz) of FGM spherical shell $\left(R = 1\,\mathrm{m}, \frac{h}{R} = 0.05, \Phi_0 = 15^\circ, \Phi_1 = 90^\circ\right)$

k	Mode number	C-C	
		Present	Ref. (Qu 2013)
0.6	1	873.65	873.71
	2	888.21	888.28
	3	893.72	893.73
	4	908.61	908.68
5	1	862.58	862.63
	2	866.82	866.84
	3	870.01	870.03
	4	896.71	896.77
20	1	852.03	852.12
	2	855.68	855.73
	3	858.64	858.70
	4	885.76	885.80

Table 3 A comparison of the phase velocity of the current system with various $\frac{A_p}{A}$, and $\frac{R}{h}$

	$\frac{A_p}{A}$				
$\frac{R}{h}$	0	0.25	0.5	0.75	1
10	713.7728	708.6180	703.2810	697.7413	691.9746
20	352.4878	349.3870	346.0946	342.5696	338.7538
30	233.4664	231.1212	228.5584	225.6956	222.3736
40	174.3283	172.3846	170.1859	167.5653	163.9487

4.3 Parametric result

In the following section dependency of the phase velocity on different geometrical and material parameters are presented and discussed Table 3 presents effects of geometrical aspect ratio of ball radius to the wall thickness R/h and A_p/A on the phase velocity. It is clear that increase in the ratio R/h decreases the phase velocity of the soccer ball such that 300% increase in this parameter causes 76% reduction in the phase velocity value for $\frac{A_p}{A} = 0$ value. On the other hand, increase in the A_p/A reduces the magnitude of phase velocity slightly.

Table 4 provides the influences of geometrical span angle ϕ_0 and A_p/A on the phase velocity. It is obvious that increase in the angle ϕ_0 decreases the phase velocity of the soccer ball such that increase from 140° to 170° in this angle causes 17% reduction in the phase velocity value for $\frac{A_p}{A} = 0$ value. On the other hand, increase in the A_p/A slightly reduces the magnitude of phase velocity for all values of angle ϕ_0.

Internal pressure of the soccer ball is also influential in determining the phase velocity as presented in Table 5. Increase in the internal pressure P from 0.5 MPa to 2.5 MPa reduces the phase velocity about 8% on average. Effects of pressure rise on the phase velocity is more intense in the lower values of span angle ϕ_0. Effect of variation in span angle on the ball model is similar to the Table 4.

Concurrent effects of internal pressure and parameter A_p/A of the soccer ball are provided in Table 6. Increase in the internal pressure P from 0.5 MPa to 2.5 MPa reduces the phase velocity about 8% in $\frac{A_p}{A} = 1$ and about 1% at $\frac{A_p}{A} = 0.2$. Effects of pressure rise on the phase velocity is more intense in the higher values of A_p/A. Effect of variation in A_p/A on the ball model is similar to the Table 4 with slight decrease in the phase velocity in higher values of A_p/A.

Table 4 A comparison of the phase of the current system with various $\frac{A_p}{A}$, and $\emptyset_o$

	$\frac{A_p}{A}$				
$\emptyset_o$	0	0.25	0.5	0.75	1
140	856.1249	849.5366	842.6429	835.4105	827.8014
150	800.3388	794.5358	788.4930	782.1854	775.5839
160	761.9335	756.6742	751.2153	745.5350	739.6080
170	713.7728	708.6180	703.2810	697.7413	691.9746

Table 5 A comparison of the dimensionless frequencies of the current system with various P, and $\emptyset_o$

	P [MPa]				
$\emptyset_o$	0.5	1	1.5	2	2.5
140	842.6429	827.8014	811.2697	792.6015	771.1723
150	788.4930	775.5839	761.3594	745.4749	727.4384
160	751.2153	739.6080	726.8876	712.7370	696.6840
170	703.2810	691.9746	679.6401	665.9719	650.5159

Table 6 A comparison of the phase velocity of the current system with various $\frac{A_p}{A}$, and P

	$\frac{A_p}{A}$				
$P\ [MPa]$	0.2	0.4	0.6	0.8	1
0.5	711.7316	709.6629	707.5658	705.4389	703.2810
1	709.6629	705.4389	701.0907	696.6070	691.9746
1.5	707.5658	701.0907	694.3102	687.1787	679.6401
2	705.4389	696.6070	687.1787	677.0250	665.9719
2.5	703.2810	691.9746	679.6401	665.9719	650.5159

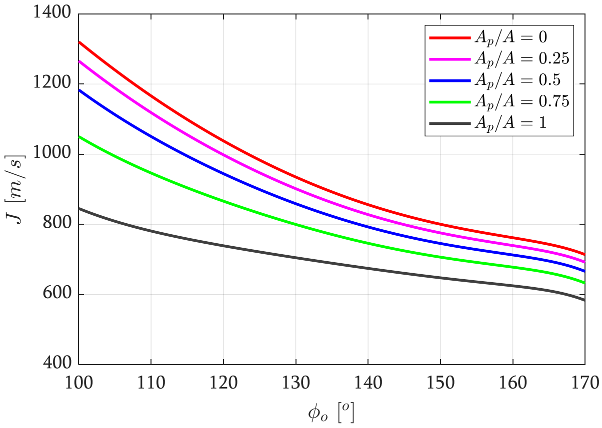

Fig. 2 A comparison of the phase velocity of the current system with various $\frac{A_p}{A}$, and $\emptyset_o$.

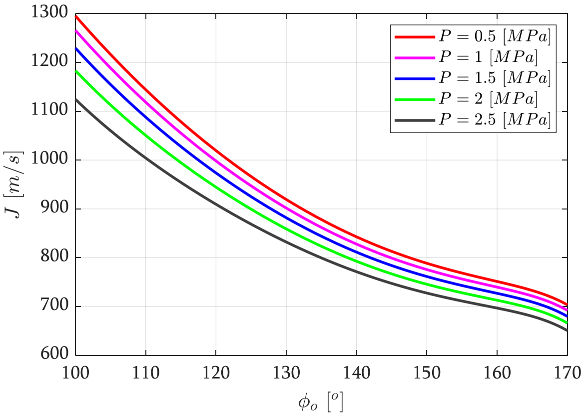

Fig. 3 A comparison of the phase velocity of the current system with various P, and $\emptyset_o$

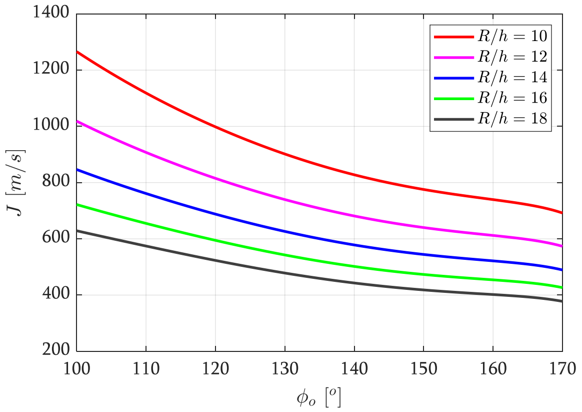

Fig. 4 A comparison of the phase velocity of the current system with various $\frac{R}{h}$, and $\emptyset_o$.

Curves of the phase velocity versus span angle ϕ_0 is depicted in Figs. 2 to 5 for different other parameters. General features of all these curves are the decreasing nature of the phase velocity with increase in the model's span angle ϕ_0. The slope of the curves is higher in the lower values of angle ϕ_0 indicating the more influence of this parameter up to ~140°. After that the influence of the span angle decreases with slight reduction in the phase velocity. Fig. 2 also shows the effect of the A_p/A parameter on the phase velocity curves. It is seen that increase in the value of A_p/A reduces the phase velocity in all values of the span angle given in this figure. In addition, effect of this parameters on the phase velocity in the lower values of ϕ_0 is more obvious than the higher values.

Fig. 3 presents the effect of the internal pressure P on the phase velocity versus span angle ϕ_0 curves. It is seen that increase in the value of P reduces the phase velocity in all values of the span angle given in this figure. In addition, effect of this parameters on the phase velocity in the lower values of ϕ_0 is slightly higher than the higher values of span angle.

Fig. 4 demonstrates the effect of geometrical aspect ratio R/h on the phase velocity curves. It could be noticed that increase in the value of geometrical aspect ratio R/h reduces the phase velocity in all values of the span angle provides in this figure. In addition, effect of this parameters on the phase velocity in the lower values of ϕ_0 is more obvious than the higher values.

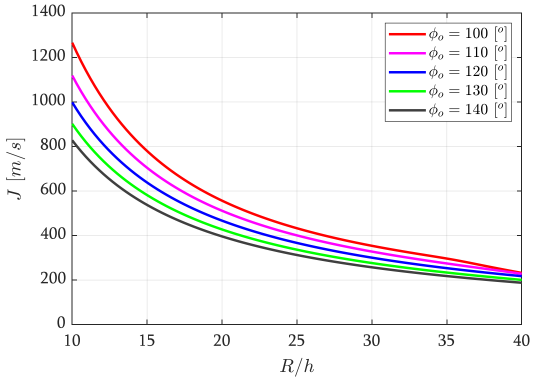

Fig. 5 A comparison of the phase velocity of the current system with various $\frac{A_p}{A}$, $and\ \emptyset_o$

5. Conclusions

In this regard, the wave propagation in soccer ball is examined in the current study using large deformation shear deformable formulations. Classical relations of stress-strain components are taken into consideration along with minimum total energy principle. The final derived relations were solved by using harmonic differential quadrature method. The results are generally presented ion term of phase velocity as function of different influencing parameters of the materials, geometry and mass of the ball.

- Increase in the angle ϕ_0 decreases the phase velocity of the soccer ball such that increase from 140° to 170° in this angle causes 17% reduction in the phase velocity value for $\frac{A_p}{A} = 0$ value
- It is seen that increase in the value of A_p/A reduces the phase velocity in all values of the span angle.
- Effect of this parameters on the phase velocity in the lower values of ϕ_0 is more obvious than the higher values.
- In higher value of ratio R/h, the effect of variation in span angle on the phase velocity could be neglected.

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