Research on the Integration of Bionic Geometry Modeling and Simulation of Robot Foot Based on Characteristic Curve

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Abstract: The bionic research of shape is an important aspect of the research on bionic robot, and its implementation cannot be separated from the shape modeling and numerical simulation of the bionic object, which is tedious and time-consuming. In order to improve the efficiency of shape bionic design, the feet of animals living in soft soil and swamp environment are taken as bionic objects, and characteristic skeleton curve, section curve, joint rotation variable, position and other parameters are used to describe the shape and position information of bionic object's sole, toes and flipper. The geometry modeling of the bionic object is established by using the parameterization of characteristic curves and variables. Based on this, the integration framework of parametric modeling and finite element modeling, dynamic analysis and post-processing of sinking process in soil is proposed in this paper. The examples of bionic ostrich foot and bionic duck foot are also given. The parametric modeling and integration technique can achieve rapid improved design based on bionic object, and it can also greatly improve the efficiency and quality of robot foot bionic design, and has important practical significance to improve the level of bionic design of robot foot's shape and structure.

1. Introduction

The design of robot foot working in field environment is of great significance to its performance of running efficiency and anti-sinking. Many researchers have studied the bionic design problem of the foot of ostrich, camel and gecko, and based on bionic design approach, new mechanical structure has been established according to the structure of the animal's feet, of which Ji [1-2] has designed walking mechanism according to the structural characteristic of camel's foot, and Yang [3] has designed the wheel of mars rover based on plantar morphological characters of ostrich's foot. The geometric bionics is an important content in bionic research. At present, the main idea of bionic research is to make a sample similar to the bionic object after measurement and improve the prototype after physical experiment [4-9]. But the process needs much time and high cost, and it is difficult to obtain the optimal scheme of bionic design. With the help of numerical simulation technology, finite element method can be used to replace experiment in some extent. One can reduce the time of experiment, and reduce the cost and shorten design cycle by simulation. However, because the shape of bionic object is usually very complex, the process of geometric modeling and mesh generation is tedious, which restrict the important of the efficiency and quality of bionic design.
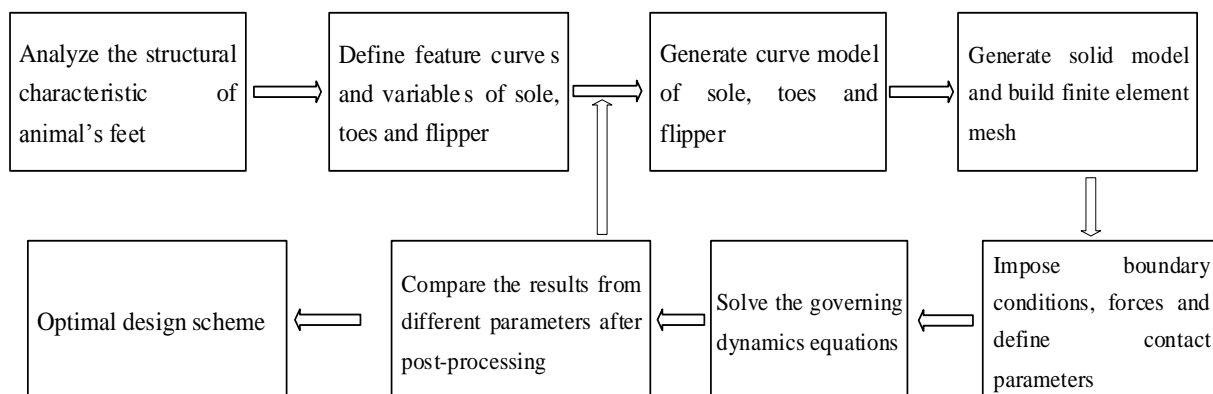
Aiming at the deficiency of existing bionic design method, the bird's feet living in soft soil and swamp environment will be taken as researching object, and considering the flexibility of design, and the efficiency of modeling and simulation, a parametric model, which is mainly made up of characteristic of skeleton and section curves, is established with ABAQUS and the integration of

geometric modeling, finite element simulation and optimization is implemented to improve the efficiency of bionic design.

2. Integrated framework of bionic geometric modeling and simulation

Bionic foot's geometric modeling is the process of building a geometric model that can represent the structural characteristic of animal's foot similar to the structure of animal's foot in shape. Figure 1 shows the integrated framework of bionic geometric modeling and numerical simulation. The structural characteristics of animal's foot are analyzed in order to find the most suitable characteristic curves and variables that can be used to define the shape of foot, toes and flippers, and then the model made up of curve network is generate to describe the shape features of foot. After creating surface model based on foot's curve network, solid model is generated and finite element meshes of foot and soil are built. In order to deal with larger deformation problem, Multi-material Arbitrary Langrage Euler method is used to describe the displacement field of soil. Then the displacement boundary conditions of soil and foot are imposed, and soil's gravity force, foot's load-bearing capacity is applied, and contact parameters between soil and foot are also defined. The results are outputted after solving the governing dynamics equations, and compare the results from different parameters after post processing; if the new results is not better than the results from the parameters used before, they should be adjusted, and then generate a new foot model with the new parameters. Repeating the above process until the best results that can be accepted are found. With the framework described in figure1, the integration of bionic geometric modeling and simulation can be implemented, and the optimization can be realized automatically. The most important part in the integrated framework is to define the characteristic curves of each part accurately, which can create more reasonable models and lay the foundation for the follow-up process. In this investigation the integrated framework is implemented in Abaqus with Python language.
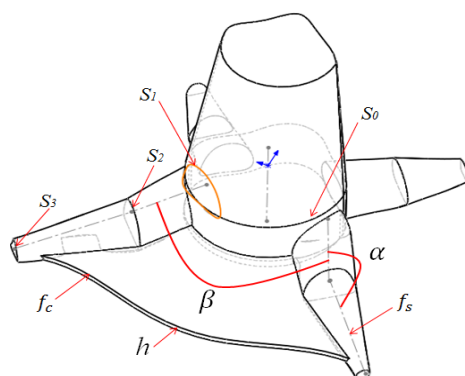

Figure 1. Integrated framework of integration of bionic foot's geometric modeling and sinking simulation.
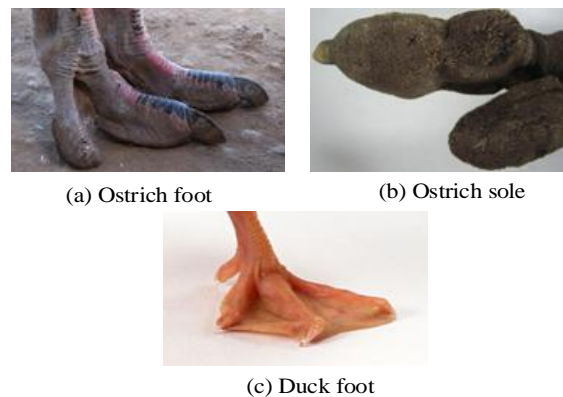
3. Geometric model of bionic foot

There are many different species living in diverse environments, for example there are crocodiles and cranes in the swamp, ducks and frogs in soft soil, and camels, ostrich and other animals in the desert. They are evolved over long periods of time in nature and have strong abilities to adapt to various terrains. Nowadays, many domestic and foreign scholars have studied the structures of animal's feet [10-12], and one of them has applied bionic ideas to the research of anti-sinking. Many animal's feet is a very helpful to inspire the research of anti-sinking, of which ostrich and duck is very representative. Their feet structural features are mainly supported by toes that are connected together by flippers. Therefore, this paper chooses these two representative animals' feet to demonstrate ours bionic geometric modeling method, and use the modeling into the integrated framework.

3.1. Geometric modeling principle of bionic foot

The geometric models of the bionic feet are created according to the similar structural features of animal's foot. The bionic foot geometry model mainly includes three parts, which include sole, toes and flippers. The geometric model of the bionic foot is shown in figure2. The detailed modeling steps are as follows: firstly, the foot section curve S_0 is defined, which can be used to generate the sole of the foot; creating the toe skeleton curves f_s which is mainly used to define the shape of phalanxes and control the rotation angle between toes. Secondly, different toe section curves S_1, S_2, S_3 should be defined according to the skeleton curves. At the same time, the rotation angle variable β between toes and the rotation angle variable α at joints need to be defined. Thirdly, the model of flipper whose characteristic curve f_c is sketched on the plane that parallels to sole plane and the thickness h of flipper also is defined at the same time.

Figure 2. Conceptual model of bionic foot.

(a) Ostrich foot

(b) Ostrich sole

(c) Duck foot

Figure 3. Ostrich foot and duck foot.

3.2. Structure characteristics of ostrich foot and duck foot.

Ostrich foot and duck foot are shown in figure 3, of which ostrich foot shown in figure 3a and 3b has only two toes [13], and they are third toe and fourth toe. The third toe is relatively developed, and the fourth toe plays a role of supporting the body when walking. The third toe and fourth toe are connected with a flipper. Because the ostrich lives in desert and wilderness areas, the soles of the feet, and the third toe, often contact with the sand. After a long time evolution, its sole has formed a unique plantar surface. As figure3c shown, duck foot has four toes, three of which are relatively long. The three longer toes are connected with flippers. The shorter toe plays a role of balance and support.

3.2.1. Geometric modeling of bionic ostrich foot. The toes of ostrich directly contact with sand, so the shape and structure of ostrich toe is important to the sinking property and walking efficiency of ostrich. The definition of ostrich's toes are based on its characteristic curves and section curves, and these curves are defined by a series of interpolation points or control points. The surface of toes can be built by sweeping the section curves S_i (i =1, 2, 3…) of toe along its skeleton curve f_s. The two toes of ostrich's feet do not have phalanx, and the modeling method of the third and fourth toes are the same.
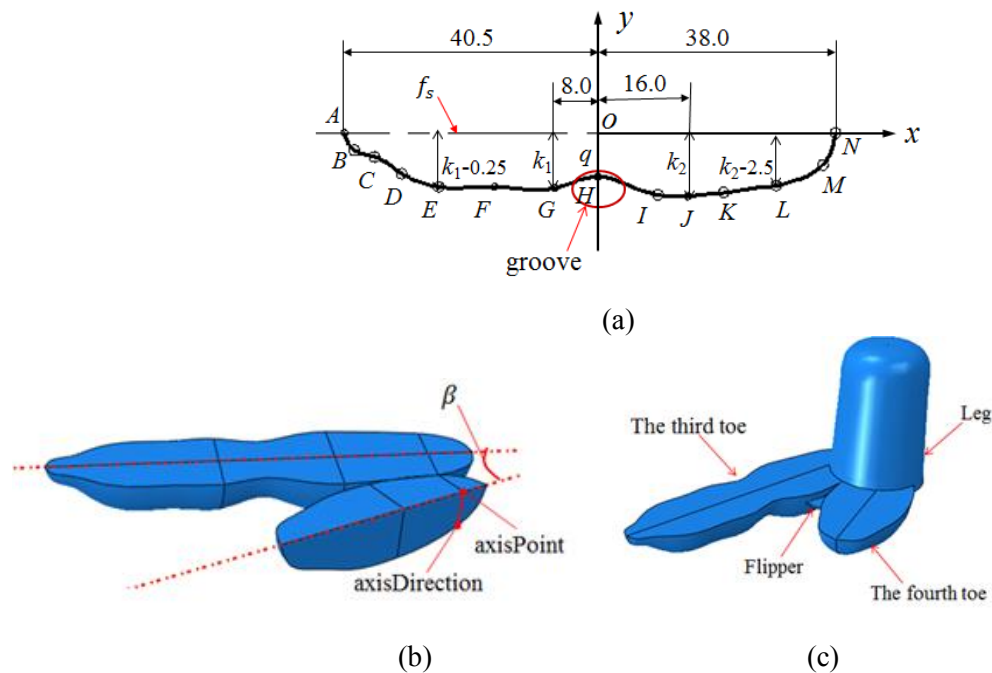
Figure 4(a) gives the shape of feature curves of the third toe, which can be defined by the coordinates of fourteen points from A to N. The y coordinates of the lowest points G and J together with the highest point H in the middle groove are taken as basic parameters, which are denoted by k_1, k_2 and q respectively. The curve describing the section of bionic ostrich toe is defined in Abaqus with Python, the code is as follows:

```
s.Spline(points=((-40.5, 0.0), (-39.25, 2.5), (-35.5, 3.9), (-31.75, k1-2.75), (-24.25, k1-0.25), (-16.0, k1-0.4), (-8.0, k1), (0, q), (8.0, k2-0.5), (16.0, k2), (24.0, k2-1.0), (32.0, k2-2.5), (37.0, k2-6.25), (38.0, 0.0)))
```

The shape of toe's section curve can be modified by changing the value of k_1, k_2 and q. Combined with section curves, the bottom surface of bionic ostrich toe can be created by sweep method. While

we give a simple model that is built by directly revolving the feature curve around the axis. The corresponding Python code is as follows:
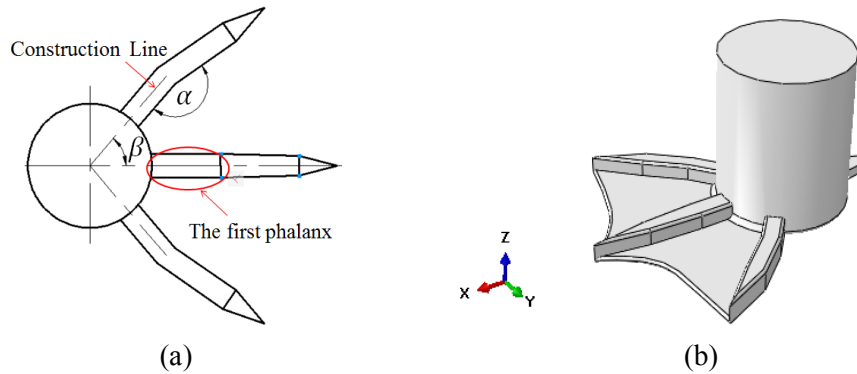
```
s.Line(point1=(-40.5, 0.0), point2=(38.0, 0.0))
s.VerticalConstraint(entity=g[4], addUndoState=False)
p=mdb.models['Model-1'].Part(name='Part-dajiaozhi',dimensionality=THREE_D, type =
DEFORMABLE_BODY)
p = mdb.models['Model-1'].parts['Part-dajiaozhi']
p.BaseSolidRevolve(sketch=s, angle=180.0, flipRevolveDirection=OFF)
a.rotate(instanceList=('Part-xiaojiaozhi-1', ), axisPoint=(0.0, y₁, 0.0), axisDirection=(0.0, 0.0, z₁),
angle= β )
```


(a)

(b)   (c)

Figure 4. Geometric models of ostrich.

Where β is the rotation angle variable that is used to define the relative posture between two toes' skeleton curves. When β equals -25°, and y_1 equals -12.50mm, and z_1 equals 6.91mm, the corresponding toe model is generated as figure 4(b) shown. After creating the flipper, the sole, toes and flipper should be assembled in Abaqus. The whole structure of bionic ostrich foot is shown in figure 4(c).

3.2.2. Geometric modeling of bionic duck foot. The modeling of bionic duck's foot is simpler than that of ostrich's foot, and the geometric modeling steps of bionic duck's foot is similar to that of ostrich's foot. Each toe of bionic duck's foot is divided into three phalanxes, and there is no parameter defined between the second phalanx and the third phalanx. Figure 5(a) shows the toes skeleton curve of duck's foot and the shape of toes of the two-dimensional shape.

(a)   (b)

Figure 5. Geometric models of ostrich.

The following code segment only shows the rotation angle variable β of toes and the rotation variable α at toe's joint.

```
s1.ConstructionLine(point1=(0.0, 0.0), point2=(2.21, 0.0))
s1.HorizontalConstraint(entity=g[3], addUndoState=False)
```

Three construction lines should be created by using above code, which control the rotation angle of three toes. So the rotation angle β of three toes will be changed by adjusting the rotation angle between construction lines.

```
s1.AngularDimension(line1=g[4],line2=g[3],textPoint=(x1, y2), value= β ))
s.AngularDimension(line1=g[19],line2=g[10],textPoint=(x2, y3), value=162.0)
s.delete(objectList=(d[0], ))
s.AngularDimension(line1=g[19],line2=g[10],textPoint=(x3, y4), value= α )
```

The rotation of toes can be controlled by changing the rotation angle β, and the rotation of phalanxes can be controlled by changing the rotation angle α. It should be noted that the fixed constraints should be defined between the second phalanx and the third phalanx. Bionic duck foot model is shown in figure 5(b).
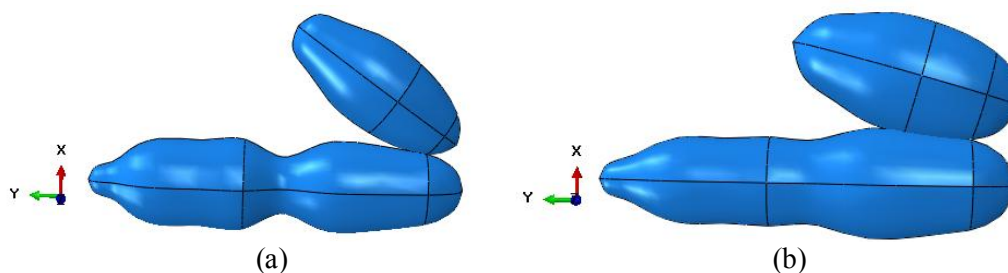
4. Simulation results and discussion

4.1. Parametric foot with different parameters

The bottom surface of the toe is directly contact with soil, so the toe's structure is very important to the study of anti-sinking. The parameters are used to establish different toe models are q, k_1 and k_2, h_1 and h_2, of which k_1 and k_2 are used to control the third toe's shape curve, h_1 and h_2 are used to define the fourth toe's shape curve. Two different values are taken for each parameter, which are given in Table 1. After the parameters are modified, the parameterized code is directly imported into Abaqus, and the models from two groups of parameter are generated automatically as figure 6 shown.

Table 1. Different values of each parameter.

Parameter	q/(mm)	k_1/(mm)	k_2/[mm]	h_1/[mm]	h_2/[mm]	β/[°]
Group 1	6	9.5	9.5	9.0	16.5	-35
Group 2	8	8.0	10.5	11.0	19.0	-15

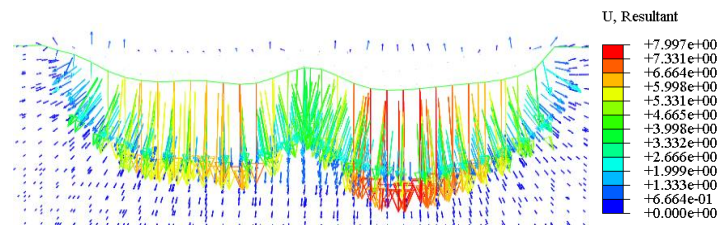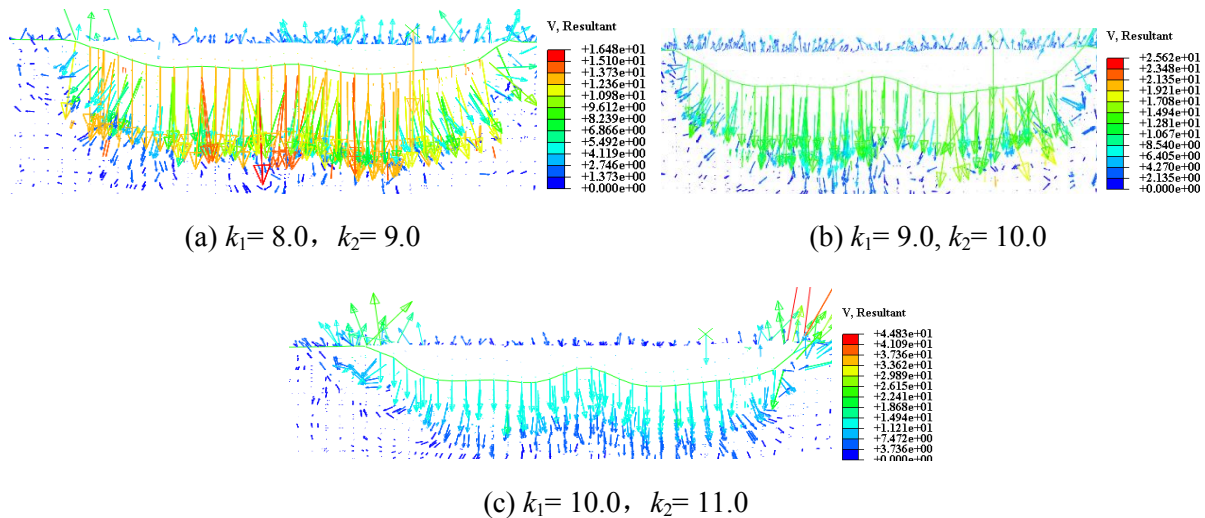(a)   (b)

Figure 6. Parametric foot with different parameters.

Parametric method can be used to build different models by quickly adjusting the model's parameters. This lays the foundation for the simulation and optimization of the foot structure, and it is easy to realize the integration of modeling and simulation of the bionic foot in the environment of Abaqus with Python language. It should be noted that the absolute changing amount of the parameters should not be too large, otherwise it will lead to a model with impractical dimensions.

4.2. The influences of parameters k_1, k_2 and q.

In order to study the influence of the values of k_1 and k_2 on the sinking property of bionic foot, the results of displacement and velocity of soil under the bionic foot are analyzed in this section. Figure 7 shows the displacement of soil when k_1 and k_2 are 9.0 and 10.0 respectively. The maximum displacement of soil is locating at the lowest point at the bionic foot's bottom surface, and at the center of the groove, the displacement of soil is relatively lower. Figure 8 gives the velocities of soil under different values of k_1 and k_2. We can find that the maximum value of soil's velocity increases with both the values of k_1 and k_2, but the differences on the average velocities of soil under the bottom of bionic foot are small, and the whole distribution of the soil's velocities are similar.

Figure 7. Displacement of soil under the foot.

(a) k_1= 8.0，k_2= 9.0

(b) k_1= 9.0, k_2= 10.0

(c) k_1= 10.0，k_2= 11.0

Figure 8. The velocities of soil with different value of k_1 and k_2.

The sinking characteristics of the bionic ostrich foots with different groove dimension in the toe section curve S_7 is compared by changing the value of q from 6.0 to 8.0. Three toe models are built by Python code to simulate the sinking process, and the results force and sinkage are compared in figure 9. It can be seen from figure 9 that the overall trends of three curves are the same, but under the same force, when q is 6mm, the sinkage is the minimum.
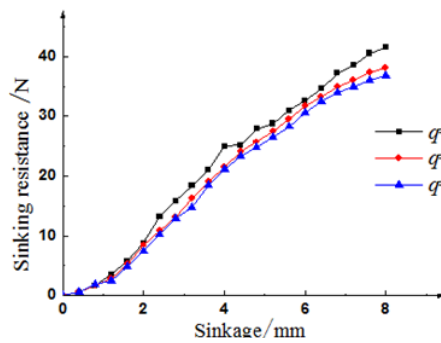
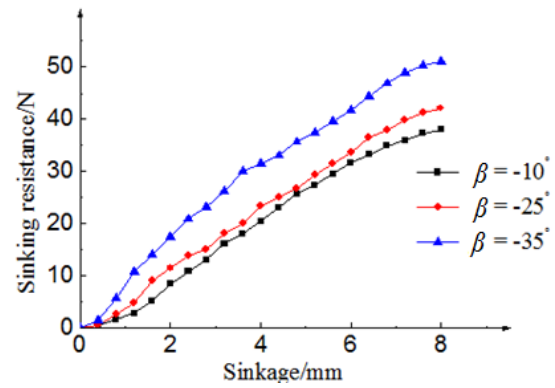**Figure 9.** Sinking characteristics at different *q*.   Figure 10. Sinking curves with different β.

4.3. Influence of parameter $\boldsymbol{\beta}$.

Figure 10 compares the sinking curves of the bionic ostrich foots when β is assigned the value of -10°, -25° and -35° respectively, which shows that when β equals -35° the sinkage is the smallest under the same sinking resistance. Figure 11 gives the stress distributions of soil with different values of β, and it can be found that when β is -10° , the maximum stress are smaller than that of other two angles, but the overall stress distribution is similar. If more values of β is assigned, we can reach a more meaningful result for the reference of the design of the bionic ostrich foot after comparing the results carefully.
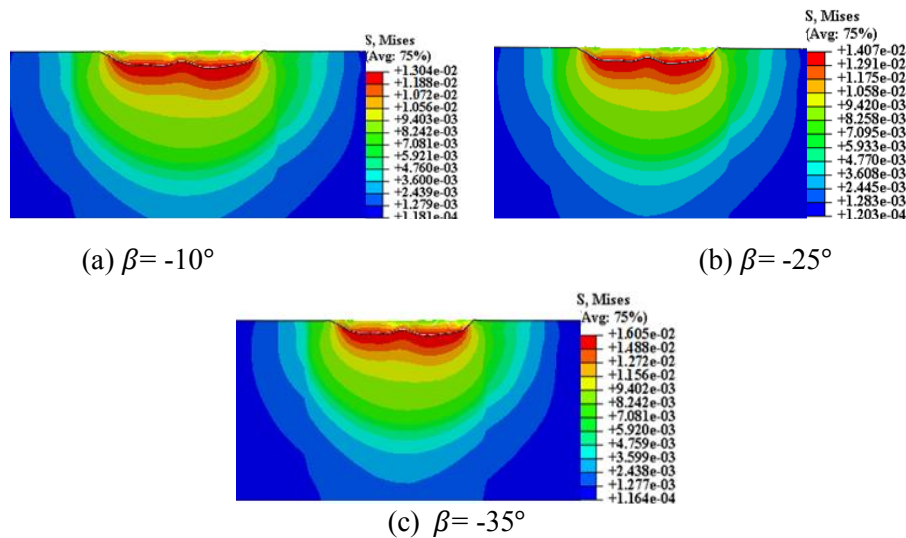

(a) β= -10°   (b) β= -25°

(c) β= -35°

Figure 11. Soil's stress distribution with different values of β.

5. Conclusion

In this paper, the feet of animals living in soft soil and swamp environment are taken as bionic objects. Characteristic skeleton curve, section curve, joint rotation variable, position and other parameters are used to describe the shape and position information of bionic object's sole, toes and flipper. The geometric modeling of bionic object is created by using the parameterization of the characteristic and section curves and variables. Based on this, the integration of parametric modeling and finite element modeling, dynamic analysis of sinking in soil and post-processing of bionic ostrich foot and bionic duck foot is implemented, and the detailed integration framework of the modeling of bionic geometric model and simulation is given. The bionic designs of ostrich and duck's feet are also introduced as an example, and the simulate results show that our method of parametric modeling and simulation is

feasible and efficient, which can achieve rapid improvement design based on geometric bionic methods. In order to improve the optimization efficiency of bionic design, in the next step we will consider make ABAQUS integrate into the framework of Isight.

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