How woodpecker avoids brain injury?

C W Wu, Z D Zhu and W Zhang

State Key Lab of Structural Analysis for Industrial Equipment, Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

Email: wei.zhang@dlut.edu.cn

Abstract. It has long been recognized that woodpecker is an excellent anti-shock organism, as its head and brain can bear high deceleration up to 1500 g under fast pecking. To investigate the mechanism of brain protection of woodpecker, we built a finite element model of a whole woodpecker using computed topography scanning technique and geometry modeling. Numerical results show that the periodical changing Young’s modulus around the skull affects the stress wave propagation in head and makes the stress lowest at the position of the brain. Modal analysis reveals the application of pre-tension force to the hyoid bone can increase the natural frequency of woodpecker’s head. The large gap between the natural and working frequencies enable the woodpecker to effectively protect its brain from the resonance injury. Energy analyses indicate the majority of the impact energy (99.7%) is stored in the bulk of body and is utilized in the next pecking. There is only a small fraction of it enters into the head (0.3%). The whole body of the woodpecker gets involved in the energy conversion and forms an efficient anti-shock protection system for the brain.

1. Introduction

Woodpeckers have excellent anti-shock ability to adapt high-speed and high-acceleration pecking activities. Many observations have showed that the woodpecker pecks at a frequency of 18–28 Hz with a maximum speed 5–7 m/s, and the maximum deceleration of a collision in less than one millisecond can reach 600–1500 g \[1-3\]. The special anti-shock and energy-absorption function have received much attention, and numerous efforts have been devoted to understand the mechanism. Gibson \[4\] compared the woodpecker’s head structure with human being’s, and found that small sized head, short impact duration and large contact area between brain and skull can protect the brain from damage of shock. Zhou et al. \[5\] dissected a grey woodpecker and found that the hyoid, which is the specific structure of woodpecker, has excellent mechanical properties with Young’s modulus of 3.72 GPa and tensile strength of 131 MPa. The hyoid, with one end fixing on the right nostril and the other end binding the skull tightly and stretching out from the mouth, is four times longer than the beak, and
the binding of the hyoid to the skull reduces the impact stress in the head [6].
To study the impact response of the woodpecker head, numerical simulations of finite element (FE) were introduced. Oda et al. [7] set up a stereo lithography head model which is three times larger than the actual head, and measured the strain in different positions in the head. Then a 2D FE model was built and proved that little cerebral liquid and the existence of hyoid bone can effectively protect its brain from shock damage. Wang et al. [8] experimentally obtained the pecking force of the woodpecker was about 8 N, which is useful for numerical simulation. They built a 3D FE model of the woodpecker head based on micro-computed topography (CT) scanning and compared the results of three models with different lengths of beaks when impacting the rigid wall. They explained that the majority of the pecking force was carried by the low beak to the neck and the brain avoided being hurt. Zhu et al. [9] observed that the upper beak is longer than the lower one and interpreted the mechanism of anti-shock in terms of stress wave propagation. They established a 3D FE model of the woodpecker head including the contact relationships among the inner structures, and studied the dynamic response of the head on pecking trees. They concluded that the stress wave mainly propagated from the upper beak and the head structure and the hyoid helps spreading the stress wave, the viscoelasticity of biomaterials is responsible for the decrease of the stress value.

To date, however, the papers published in the literatures merely focus on the stress and strain analyses of a sole woodpecker head under a single impact. Little is known on the frequency response of the head and dynamic response under successive process of pecking. In light of these we herein built a whole woodpecker model including the body based on the CT scanning technology. Different from the existing single head model, the whole model has the advantages as follows: (i) Constraints can be applied at the claws and tail, where are far away from the brain. Thereby the effect of localized stress concentration initiated by constraints could be reduced dramatically; (ii) The successive pecking process is more close to the actual pecking of woodpecker, which could truly reflect the distribution and accumulation of stress. Based on this model, the anti-shock characteristic of the woodpecker was studied from the aspects of modal analysis, stress spectrum analysis and energy analysis.

2. Material property
The woodpecker skull is a small and spheroid-like structure and it is hard to obtain the mechanical property by conventional tension test. In this paper we used nano-indentation equipment (Triboindenter, Hysitron TI-950, Hysitron, USA) to obtain the property of skull [10-12]. Twenty-eight samples with the average size of 2.5 mm×2.5 mm were cut from the skull and washed with deionized water. Then the sample was indented with a trapezoidal load function from 50 μN to 1,250 μN. Figure 1 shows the positions of the samples on the sagittal section of the woodpecker head and the local Young’s modulus measured by nano-indentation. The results showed that the Young’s modulus changed ups and downs with the average value of 6.6 GPa and the coefficient of variation of measured Young’s modulus of each specimen ranges from 16% to 40% [13, 14].
The Young’s modulus of woodpecker skull has large standard deviation and changes in sinusoidal form. How the changing modulus will affect the stress wave propagation in the skull when woodpecker pecks? Limited by the huge amount of the meshes in the head, it is difficult to discuss the effect in the actual head model, thus we built a simplified model of a viscoelastic bar. Figure 2 shows the model of stress wave propagation in the viscoelastic bar. The bar is 2,000 mm long and divided
into three parts including incident part, material changing part and ending part. A projectile strikes at
the start of the bar with the velocity of 7 m/s, and the boundary condition of the bar is complete free.
We suppose the bar has similar material property with the bone and the material changing of the
middle part is in sinusoidal form. Equations (1) and (2) give the viscoelastic property of the bar.

![Figure 1](image1.png)

**Figure 1.** Positions of the samples on the sagittal section of the woodpecker head and the local
Young’s modulus measured by nano-indentation, the average distance between the adjacent samples is
2.5 mm.

![Figure 2](image2.png)

**Figure 2.** The model of stress wave propagation in the viscoelastic bar. The bar is impacted by a
projectile with the velocity of 7 m/s in one end, the mass of the projectile is 50 g and the mass of the
bar is about 600 g. The bar is divided into three parts including incident part, material changing part
and ending part. The curves in the middle shows three situation of different Young’s modulus and
viscosity assigned in the material changing part.
\[ E = E_0 + E_a \sin\left(2\pi \frac{kx}{l} + \varphi_k\right) \]  

(1)

\[ \eta = \eta_0 - \eta_a \sin\left(2\pi \frac{kx}{l} + \varphi_\eta\right) \]  

(2)

\(E_0\) and \(\eta_0\) represent the average values of the Young’s modulus and viscosity, which are 10 GPa and 2 Pa·s respectively. \(E_a\) and \(\eta_a\) are the changing amplitude of them, with the maximum value of 7.5 GPa and 1.5 Pa·s. According to the amplitudes of the material parameter assigned to the middle part, we set three computational situations totally. In addition, \(k\) and \(\varphi\) represent the cycle count in the specify distance (\(l=1000\) mm) and phase delay. When the cycle count is large enough, the effect of phase delay could be negligible. Bone with higher Young’s modulus usually contains less water. As a result, the viscosity variation of skull should demonstrate the opposite trend with respect to the Young’s modulus.

\[ \text{Figure 3. Material parameters assigned in the middle bar and the peak stress curves of the whole bar.} \]

The peak stress curve is composed of the maximum stress in the impact direction at different moment along the bar. The red line represents stress curve of the bar when uniform material property assigned in the middle bar. The curves have the same variation in the incident segment but change fiercely in the middle segment. From Fig. 3 we could find that the peak stress changes in agreement with the changing of the Young’s modulus. The stress is large in the high-modulus zone and small in the low-modulus zone. In Figure 3, take the maximum amplitude of
the material parameter as an example, the peak stress is 25.7 MPa in the increasing segment which is 14.7% higher than the uniform distribution of material property and 14.8 MPa in the decreasing segment which is 31.8% lower than the uniform one. Therefore, the variation of the material parameter indeed affects the propagation of the stress wave and makes the peak stress smaller in the low-modulus zone than the other positions. The same conclusion can be deduced under multi-periodic conditions (where \( k > 1 \)), and the peak stress in the final period of the material property will be the smallest in the whole bar.

For the woodpecker head, stress wave is generated by pecking at the tip of beak, and is propagated into the brain through the skull. In the direction of stress wave passing, as measured, the Young’s modulus of the skull changed periodically as shown in Figure 1. Here we provide an analogy between the woodpecker head and the viscoelastic bar model as shown in Figure 4. The beak works as the incident segment of the head to make the impact stress steady, and the skull reacts as the material changing part to reduce the stress in the brain. Figure 4a shows the peak stress curve of the whole bar when material parameter changes in two periods and Figure 4b shows the changing of measured modulus of the skull on the sagittal section. According to the conclusion of the former analysis, we deduce that the peak stress of skull is smallest at the position of the brain, which is the final low-modulus zone of the material property in the skull.

**Figure 4.** An analogy between the woodpecker head and the viscoelastic bar model. (a) The peak stress curve of the whole bar when material changes in two periods (\( E_a = 7.5 \) GPa, \( \eta_a = 1.5 \) Pa·s and \( k = 2 \)), and the arrow points is the position of the smallest peak stress in the bar; (b) The changing of the measured modulus on the sagittal section, there are two cycles of the modulus in the curve and brain is located at the final low-modulus zone of the material property in the skull.

3. **FE model**
The woodpecker investigated here is a female grey-faced one widely living in the Northern China. Woodpecker usually has small head, little amount of cerebrospinal fluid, big eyeballs, hard beaks and
long flexible hyoid bone \cite{15}. For this kind of bird, the hyoid bone is three or four times the length of the beak with one end fixing on the right nostril and the other end binding the skull tightly and stretching out from the mouth to reinforce the head. In order to get an accurate finite element (FE) model including these features, the procedure is as follows. The woodpecker was put on a CT scanning device (CT scanner, LightSpeed VCT XT, GE, USA) and the inner structure of head can be discerned through the CT images without breaking their outer parts \cite{16-18}. Then Mimics and ProE software were used to establish 3D geometric configurations by integrating the scattered points of the images. After the geometric repairs, the FE model meshed by tetrahedron elements was established using Abaqus software.

Figure 5. FE model of a whole woodpecker, the woodpecker has 1,030,000 elements in total, and the head has more than 940,000 elements which accounts for 91\% of the total elements, the arrows show the moving direction of the head.

The final FE model contains more than 940,000 elements with a minimum size of 0.07 mm in the head, 70,000 coarse elements with a maximum size of 3.5 mm in the body and 20,000 elements with a minimum size of 0.16 mm in the trunk. Figure 5 shows the FE model of a whole woodpecker, as can be observed, the element size increases from the top of the head to the body gradually. The whole model could be divided into ten parts, the body is composed of parts named torso, wing, neck, claw and tail, and the woodpecker head is composed of parts named beak, hyoid, skull, dura and brain. The body parts are mainly composed of muscles and other elastic tissues, and thus are considered as elastic materials. The head is set as viscoelastic material to reflect the effect of brain on the stress propagation and the energy absorption. Table 1 lists the physical and mechanical parameters of the ten parts \cite{19-26}. In the FE model there are totally eighteen contact pairs and tie constraints which are set as surface to
surface contact, and the sliding formulation was finite sliding to ensure the convergence and the accuracy of simulation. For a woodpecker, the pores of the skull bone are always filled with tissue fluids. It has been verified that the biological fluids and soft tissue in the pores of the bone does not affect the bone’s modulus significantly. Thus we build a continuum model with the ignorance of pores and then assign the material properties to the whole model.

Table 1. Physical and mechanical parameters of the ten parts

| Parts  | Torso | Wing | Tail | Neck | Claw | Skull | Brain | Beak | Dura | Hyoid |
|--------|-------|------|------|------|------|-------|-------|------|------|-------|
| Volume (mm$^3$) | 51961 | 14924 | 822 | 705 | 321 | 1797 | 1230 | 180 | 143 | 31 |
| Density (mg/mm$^3$) | 1.3 | 1.2 | 1.2 | 1.2 | 3 | 1.2 | 1.04 | 1.46 | 1.04 | 1.2 |
| Mass (g) | 67.6 | 17.9 | 0.99 | 0.85 | 0.96 | 2.16 | 1.28 | 0.26 | 0.15 | 0.04 |
| Relative Mass (%) | 73.3 | 19.4 | 1.07 | 0.92 | 1.04 | 2.34 | 1.39 | 0.28 | 0.16 | 0.04 |
| Young’s Modulus (Pa) | 2.5×10$^9$ | 4×10$^9$ | 4×10$^9$ | 5×10$^9$ | 2×10$^{10}$ | 6×10$^9$ | 3.1×10$^9$ | 7×10$^9$ | 3.7×10$^9$ | 3.7×10$^9$ |
| Poisson’s Ratio | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.499 | 0.3 | 0.3 | 0.3 |
| Coefficient of Viscosity (Pa·s) | — | — | — | — | — | 0.086 | 3.85 | 0.086 | 3.85 | 0.086 |
| References | [19,20] | [21] | [21] | [19,22] | [19,23] | [19] | [24,25] | [26] | [9,25] | [5] |

*Relative mass is calculated on the mass of the whole woodpecker.

4. Modal analysis

The natural frequency is highly dependent on the material properties and boundary conditions. Herein we focus on the frequency characteristic of the head, and fixed the woodpecker’s head at the bottom of neck to simulate the actual conditions. To examine the effect of pre-tension force on hyoid, we applied different pre-tension forces to the hyoid of the model. As the maximum tension strength and the across-section area of the hyoid are reported to be about 131 MPa and 0.2 mm$^2$ respectively, we estimated the maximum pull force of the hyoid bone is around 26 N \cite{5,6}. As such, in the model, we assumed the upper limit of pre-tension force to be 25 N. With one end of the hyoid fixed on the nostril, the other end was pulled with a force of 0 N to 25 N. The first thirty modes of woodpecker head are obtained. It is found that they are the local vibration occurring within the brain due to its low Young’s modulus. The whole vibration frequency of woodpecker head must be higher than the local one.

Figure 6 shows that the first ten natural frequencies of woodpecker head are in the range of 50-100 Hz. These frequencies are more than twice the working frequency (18-28 Hz) of the woodpecker. Apparently, such natural frequencies can protect the woodpecker head from resonance damage when pecking the trees. To imitate the contract of hyoid bone of a woodpecker on pecking, we investigate the effect of the application of pre-tension forces on the natural frequencies of woodpecker’s head. As illustrated in Figure 6, the larger the pre-tension force of hyoid, the higher the natural frequency of head. Take the first natural frequency as an example, when the applied pre-tension is increased from 0
N to 25 N, the natural frequency increases from 47 Hz to 57 Hz, see the inset to Figure 6, an increment of 21.3%.

Figure 6. The first ten natural frequencies of the woodpecker head under 0 N to 25 N pre-tension force on hyoid. Illustration in the bottom right corner shows the effect of the pre-tension force on the first natural frequency of the woodpecker head, which raises the frequency from 47 Hz to 57 Hz.

5. Energy analysis

Next we will study the distribution and conversion of energy in a whole woodpecker during the successive peckings in details. When woodpecker pecks, the muscles of the neck control the motion of head towards and away from the trunk directly, and the energy stored in the body is converted from SE into kinetic energy (KE) and then is converted reversely. The total SE in the woodpecker is mainly composed of recoverable strain energy (RSE) and dissipated energy (DE) which reflect the degree of deformation and heat generation respectively.

Figure 7 shows the total strain energy of the different parts of the woodpecker. Computational results show that the strain energy stored in parts of body is much higher than that in the head. When the woodpecker head returns to the initial position after three successive peckings, the total SE stored in the body accounts for 99.7% of the whole bird, and there is merely 0.3% in the head. The stored energy will be utilized in the next pecking, and the energy enters into the head is only a small fraction of it. The circulation of energy conversion repeats itself while the head pecks trunk successively.

The strain energy in woodpecker head increases periodically due to the dissipated energy of the viscosity of materials. For the brain part, the RSE density is the lowest and the DE density is the largest which is much higher than the other parts. High dissipated energy causes the temperature increment of the brain, and the value can be calculated by Equation (3).

\[
Q = C_p m \Delta T
\]  

(3)
The total strain energy of the main parts of the woodpecker. The claws and tail are fixed on the trunk during the whole pecking process, and the energy distribution and conversion in them are affected by the constraints readily. The mechanism of energy generation is quite different from the other parts of the woodpecker, thus we do not compare the energy in them with the other parts.

Herein, $m$ presents the mass and $C_p$ is the specific heat, which was approximated as $2.18 \times 10^3$ J/kg·°C \cite{27}. The average DE density ($Q/m$) of brain during one pecking is about 12.5 J/kg. Thus, the temperature increment $\Delta T$ is found to be 0.0057°C. After one successive pecking process (10 to 30 peckings), the temperature increment of the brain will be 0.06 to 0.17°C. This theoretically explains why the woodpecker cannot conduct successive peckings for a long time, but has to take a break for heat dissipation after certain peckings. The other structures of the head such as beak, skull, hyoid and dura matter, provide energy absorption and physical protection for the brain to lower the stress and deformation of the brain further.

6. Conclusions
The woodpecker has the unique ability to protect its brain from impact damage. In this paper we studied the anti-shock mechanism of the woodpecker and got the conclusions as follows:

(a) The Young’s modulus around the skull is non-uniform but changes periodically. The results of stress wave propagation in the viscoelastic bar shows that the peak stress changes accord with the changing of the Young’s modulus and the stress is lowest in the final low-modulus zone. The material property distribution of the skull makes the peak stress smallest at the position of the brain.

(b) The application of pre-tension force to hyoid bone can increase the natural frequency of woodpecker head with the maximum increment of 21.3%. The large gap among the natural and working frequencies enable the woodpecker to effectively protect its brain from the resonance injury.

(c) Most of the impact energy is converted into the strain energy stored in the body and is utilized in...
the next pecking. There is only a small fraction of it enters into the head. The energy dissipated in the brain finally raises the temperature of the brain. This may explain why the woodpecker has to take a break after certain successive peckings.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (11272080) and the Doctoral Education Foundation of China Education Ministry (2011004110021).

References
[1] Stark R D et al 1998 A quantitative analysis of woodpecker drumming Condor vol 100 pp 350–356
[2] May P R et al 1979 Woodpecker drilling behavior Arch. Neurol. vol 36 pp 370–373
[3] Ono K et al 1980 Human head tolerance to sagittal impact Stapp Car Crash Conf. Proceedings pp 101–161
[4] Gibson L J 2006 Woodpecker pecking: how woodpeckers avoid brain injury J. Zool. vol 270 pp 462–465
[5] Zhou P et al 2009 The novel mechanical property of tongue of a woodpecker J. Bionic. Eng. vol 6 pp 214–218
[6] Yoon S H et al 2011 A mechanical analysis of woodpecker drumming and its application to shock-absorbing systems Bioinspir. Biomim. 6 016003
[7] Oda J et al 2006 Mechanical evaluation of the skeletal structure and tissue of the woodpecker and its shock absorbing system JSME Int. J. Ser. A vol 49 pp 390–396
[8] Wang L Z et al 2011 Why do woodpeckers resist head impact injury: a biomechanical investigation Plos One 6 e26490
[9] Zhu Z D et al 2012 Numerical study of the impact response of woodpecker’s head Aip. Adv. 2 042173
[10] Oliver W C et al 1992 An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments J. Mat. Res. vol 7 pp 1564–1583
[11] Pharr G M et al 1992 On the generality of the relationship among contact stiffness, contact area, and elastic modulus during indentation J. Mat. Res. vol 7 pp 613–617
[12] Oliver W C et al 2004 Measurement of hardness and elastic modulus by instrumented indentation: advances in understanding and refinements to methodology J. Mat. Res. vol 19 pp 3–20
[13] Stefan U et al 2010 Effects of three different preservation methods on the mechanical properties of human and bovine cortical bone Bone vol 47 pp 1048–1053
[14] Chen P Y et al 2009 Comparison of the structure and mechanical properties of bovine femur bone and antler of the North American elk Acta Biomat. vol 5 pp 693–706
[15] Villard P et al 2004 How do woodpeckers extract grubs with their tongues The Auk vol 121 pp 509–514
[16] Agam G et al 2005 Vessel tree reconstruction in thoracic CT scans with application to nodule detection IEEE Trans. Med. Imag. vol 24 pp 486–499
[17] Wan S Y et al 2002 Multi-generational analysis and visualization of the vascular tree in 3D micro-CT images Comput. Biol. Med. vol 32 pp 55–71
[18] Rydberg J et al 2000 Multi-section CT: scanning techniques and clinical applications. Radiographics
vol 20 pp 1787–1806

[19] Wegst U G K et al 2004 The mechanical efficiency of natural materials Philos. Mag. vol 84 pp 2167–2181

[20] Chen P Y et al 2008 Structure and mechanical properties of selected biological materials J. Mech. Behav. Biomed. Mater. vol 1 pp 208–226

[21] Cheng S et al 2009 Mechanical and thermal properties of chicken feather fiber/PLA green composites Compos. Part B Eng. vol 40 pp 650–654

[22] Meyers M A et al 2008 Biological materials: Structure and mechanical properties Prog. Mater. Sci. vol 53 pp 1–206

[23] Li B W et al 2010 Experimental study on the mechanical properties of the horn sheaths from cattle J. Exp. Biol. vol 213 pp 479–486

[24] Taylor Z et al 2004 Reassessment of brain elasticity for analysis of biomechanisms of hydrocephalus J. Biomech. vol 37 pp 1263–1269

[25] Sack I et al 2009 The impact of aging and gender on brain viscoelasticity Neuroimage vol 46 pp 652–657

[26] Seki Y et al 2005 Structure and mechanical behavior of a toucan beak Acta Materialia vol 53 pp 5281-5296

[27] Cooper T E et al 1971 Correlation of thermal properties of some human tissue with water content Aerosp. Med. vol 42 pp 24–27