Effect of acceleration on optimization of Adidas Bounce shoes

Mathew James Dicksona*, Franz Konstantin Fussa

aSchool of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne VIC 3083, Australia

Received 24 March 2011; revised 30 April 2011; accepted 2 May 2011

Abstract

Directional energy transfer is a term used to describe the phenomenon where energy is returned as force acting in a direction other than the direction in which energy was put into the system. Directional energy transfer in running shoes increases athletic performance as running speed by transferring energy to the direction of locomotion. The concept can be applied to the Adidas Bounce™ style shoe. The shoe uses tubes with a Θ-shaped cross section incorporated into the shoe sole. Directional energy transfer can be optimized if the Bounce tubes of Adidas shoes are rotated and the overall stiffness changed (by altering the tube length). There are a number of parameters that relate to directional energy transfer. These parameters are: energy transferred (as a percentage of vertical input energy); energy transferred (absolute quantity); energy returned in the horizontal direction and total system energy. The aim of this paper was to investigate whether the optimum solution changed if the runner accelerated during a stride. The simulations showed that there is very little change in optimum design angle and that if additional rearward deflection of the bounce tube is permissible performance (energy transferred and returned) actually improves when the runner accelerates.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license. Selection and peer-review under responsibility of RMIT University

Keywords: Directional energy transfer; running shoes; optimisation

1. Introduction

The term and principle of directional energy transfer was introduced by Fuss [1] for defining and describing the phenomenon where energy is returned as force acting in a direction other than the direction in which energy was put into the system. Directional energy transfer in running shoes increases athletic...
performance as running speed by transferring energy to the direction of locomotion [1]. Directional energy transfer was used as a design parameter by Dickson and Fuss [2] for shoe design optimization using an existing running shoe concept (Adidas Bounce™ tubes). The sole structure was modeled on an Ambition PB shoe. The directional energy transfer of the Adidas bounce tube was found by Fuss [1] to be zero in the shoe as manufactured in its current form. Fuss [1] showed that rotation of the tubes would result in energy transfer from vertical to horizontal (running) direction, and Dickson and Fuss [2] determined that rotation of the bounce tubes counter clockwise would maximise directional energy transfer. The transfer was expressed as a percentage (relative energy transfer, ETP). In its latest embodiment as the Adidas Bounce Titan shoe the Bounce™ concept fails to make the most of directional energy transfer. The rotation angle of the forefoot elements is in the opposite direction to that suggested by Dickson and Fuss [2]. This will result in directional energy transfer from horizontal to vertical and so reducing the speed of running.

Fig. 1. Adidas Bounce Titan shoe; notice the clockwise rotation.

The forefoot system of a Bounce tube shoe can be modelled by the equations of motion [1], [3]:

\[ F_{\text{shear}} = k_{\text{shear}} y_{\text{shear}}, \quad F_{\text{compression}} = k_{\text{compression}} x_{\text{compression}} \]  

\[ y_{\text{shear}} = y_a \cos \theta - x_a \sin \theta, \quad x_{\text{compression}} = \sin \theta + x_a \cos \theta \]  

\[ F_y = F_{\text{shear}} \cos \theta - F_{\text{compression}} \sin \theta, \quad F_x = F_{\text{shear}} \sin \theta + F_{\text{compression}} \cos \theta \]  

\[ E_y = \int F_y \, dy, \quad E_x = \int F_x \, dx, \quad E_{\text{shear}} = \int F_{\text{shear}} \, dy_{\text{shear}}, \quad E_{\text{compression}} = \int F_{\text{compression}} \, dx_{\text{compression}} \]  

\[ E_{\text{tot}} = E_y + E_x = E_{\text{shear}} + E_{\text{compression}} \]  

\[ E_{\text{trans}} = \lim E_y \]  

Here \( y_a \) and \( x_a \) denote the displacement of the sole upper surface relative to the frame of reference (positive in downward and backward direction); \( y_{\text{shear}} \) and \( x_{\text{compression}} \) denote the displacement of the vertical and horizontal springs \( E_y \) and \( E_x \) denote vertical and horizontal system energies respectively, \( E_{\text{shear}} \) and \( E_{\text{compression}} \) represent the stored energies of the horizontal and vertical springs, respectively, and \( E_{\text{tot}} \) and \( E_{\text{trans}} \) are the total system energy and the energy transferred (from vertical to horizontal direction); \( F_y \) and \( F_x \) are the forces applied to the shoe (the in downward and backward direction); \( \theta \) denotes the angular position of the Adidas Bounce tube. \( \theta \) is zero if the Bounce tube is aligned horizontally, positive rotation is a counter clockwise rotation. \( F_{\text{compression}} \) and \( F_{\text{shear}} \) are the forces and stiffness respectively (in the compressive and shear stiffness modes).

In the study by Dickson and Fuss [2] the compressive and shear stiffness of the Adidas bounce tubes from an Adidas ambition PB shoe were measured. The compressive stiffness was found to follow the equation:
\[ a_{\text{compression}} = 0.1 + 1.15x - 0.340x^2 - 0.259x^3 + 0.399x^4 - 0.170x^5 + 0.0355x^6 - 4.19E-3x^7 + 2.78E-4x^8 - 9.97E-6x^9 + 1.49E-7x^{10} \text{ N/mm per mm of tube length} \]  

(7)

The average stiffness in shear of the tube was:

\[ a_{\text{shear}} = 0.73 \text{ N/mm per mm of tube length}. \]  

(8)

The results from these tests will be used in this investigation. The force input used in this investigation is shown in Figure 2. The force used in the y direction (vertical) was the same \( F_y \) constant speed profile in both the constant speed and accelerated cases. The force to be used in the x direction (horizontal) \( F_x \) constant speed is a typical force profile for a person running at constant speed. The acceleration loading profile \( F_x \) accelerating was obtained by multiplying \( F_x \) constant speed by 1.5. This simulates the additional force required to propel the athlete faster.

While directional energy transfer expressed as a percentage is a very sensible choice of measuring the directional energy transfer, there are other possibilities. They are the absolute amount of energy transferred \( E_{\text{trans}} \), the energy returned in the horizontal direction \( E_{\text{rh}} \) and the total system energy \( E_{\text{tot}} \). These parameters of can be understood by inspection of Figure 3. The parameter of energy transfer percent is the ratio of the energy transferred to the energy input in the vertical direction.

The aim of this investigation is to determine whether acceleration of the runner affects the energy transfer parameters and what this would mean for the design of the sole. Simulation will be performed to determine the optimum solution when considering the four energy transfer parameters in both the constant speed running case and the accelerating runner case.
Fig. 3. Curves showing the energy transferred, stored, and returned in the forefoot sole structure during running. Directional energy transfer is present.

2. Method of Optimisation

By simplifying a model of the bounce tube and assuming a uniform cross section of tube throughout the shoe we can use the aforementioned model. A length based multiplier ($l$) is incorporated to the constitutive equations resulting in $k_{\text{shear}} = la_{\text{shear}}$ and $k_{\text{compression}} = la_{\text{compression}}$ where $a_{\text{shear}}$ and $a_{\text{compression}}$ denote the stiffness per unit length of tube from Eqs. (7) and (8). The assumption of uniformity means the design of a shoe is fully specified using the parameters of tube length and rotation angle. To find the solution some appropriate and sensible constraints must also be applied.

The optimum design must be constrained by the maximum allowable rearward deflection of the shoe. In this case 5 mm was chosen as the maximum to ensure runner comfort. Without such a constraint the optimum solution will involve large deflections and very short tube lengths which are beyond the physical limits of the tube. So the constraint on the feasibility is rearward maximum deflection $y_a < 5$ mm. An additional constraint of $x_{\text{compression,max}} < 4.5$ mm will also be specified. This tube compression constraint has been added to ensure that the compression of bounce tube does not exceed a level where compression stiffness reaches its local maximum peak before buckling. Solutions are also constrained by the domain in which a solution is sought. A design space was selected so that the length of tube is positive and less than 400 mm total for the shoe and angle of rotation $0 < \theta < 90$. The solutions are also constrained such that the energy transfer ($E_{\text{trans}}$) and energy return ($E_{\text{rh}}$) are positive (that is, in the correct direction from vertical to horizontal).
A model was simulated based on Eqs. (1) - (7) using the shoe input forces in Figure 2. This allows the determination of all of the energy transfer parameters of the tube system after selecting a specific length and angle. Experimental simulations with various lengths and angles can be conducted using Mode Frontier (Version 4 by Esteco, Padriciano, Italy). This allows finding the optimum for all of the parameters related to energy transfer and plot the parameter for optimisation against angle. The initial points in this space were created using the full factorial algorithm with 36491 points (91 for angle and 401 for length). The results can easily be sorted to find the optimum.

Fig. 4. The variation of the optimized solution obtained for various angles in the constant speed and accelerating runner cases.
The optimum solution for angle in both the constant speed and accelerating runner conditions are (Figure 4): relative energy transfer \( (ETP) \): 23° and 22°, \( E_{\text{trans}} \): 42° and 38°, \( E_{\text{rh}} \): 30° and 24°, \( E_{\text{tot}} \): 66° and 58°. The maximum feasible values of the appropriate parameters for various angles are shown in Figure 4. For a shoe sole optimized for constant speed, the effect of the sole subjected to forces typical of a runner while accelerating is investigated. Table 1 summarises the results.

Table 1. Comparison of design parameters for constant speed and acceleration at same tube length.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Constant speed optimum sole parameter value</th>
<th>Accelerating speed parameter value with the same sole</th>
<th>Rearward deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETP</td>
<td>21.7%</td>
<td>28.2%</td>
<td>6.5 mm</td>
</tr>
<tr>
<td>( E_{\text{trans}} )</td>
<td>718 mJ</td>
<td>965 mJ</td>
<td>6.0 mm</td>
</tr>
<tr>
<td>( E_{\text{rh}} )</td>
<td>874 mJ</td>
<td>1190 mJ</td>
<td>6.1 mm</td>
</tr>
<tr>
<td>( E_{\text{tot}} )</td>
<td>7821 mJ</td>
<td>8262 mJ</td>
<td>8.7 mm</td>
</tr>
</tbody>
</table>

4. Discussion

Having multiple parameters for design optimization makes it difficult to select one unique optimum solution. The angle and length for the optimum solutions vary considerably for the different optimisation parameters. Despite this, for all of the parameters the trend is consistent: If the shoe is optimized for the constant speed running condition then, for that shoe sole prototype, the parameter value (ETP, \( E_{\text{rh}} \), \( E_{\text{trans}} \) or \( E_{\text{tot}} \)) increases with increasing \( F_x \) and acceleration, and the optimum design angle decreases slightly. Note that rearward deflection for such a shoe sole would exceed the 5 mm rearward deflection stipulated if the sole were used in accelerating running conditions, but the same is true for running at higher speeds.

5. Conclusion

The optimization of the Adidas Bounce tube shoe is affected by athlete’s acceleration. The consideration of other parameters of interest introduces alternative best solutions for the optimum running shoe. For a shoe sole designed for constant speed running these optimum solutions show improved performance when subjected to acceleration of the runner.

References