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Dynamic modeling of a springboard during a 3 m dive

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Abstract

Analysis of springboards in elite diving have been limited to the measurement of the variation of material characteristics along the length of the board and it appears that dynamic models of the board's motion have not been carried out because of its complex nature. The purpose of this paper is to develop a simple mechanical model to (i) understand the physics of the board's motion and (ii) act as a precursor to optimizing the board to enable divers to maximize their chances of a good score.

Keywords: Modeling; Diving; Springboard

1. Introduction

Previous analysis of springboards in elite diving have been limited to the measurement of the variation of material characteristics along the length of the board using static and dynamic methods to obtain three basic parameters: spring constant, damping coefficient and effective mass (only a fraction of the springboard's total mass interacts with the diver during contact and can be considered to be lumped at a single point in contact with the diver's feet). The influence of the damping coefficient can be disregarded because damping forces are found to be insignificant during the time of board depression and recoil when compared to the much larger spring force and the inertial force of the board [1-3]. This means that the analysis has been carried out calculating only 2 parameters of the springboards. Two types of springboards were analyzed using this procedure: Duraflex [5] and Maxiflex Model B [2-4].

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1.1. Static Procedure to determine stiffness and effective mass

This has been the most used method to obtain springboard's stiffness [1-3]. From Hooke's law, the spring stiffness values for these springboards were determined by placing known loads (Olympic weightlifting discs in this case) on the board and measuring the corresponding static deflection.

Incremental loads were applied at different distances from the free end of the board. For each load-position combination, the board's static deflection was recorded for the point directly beneath the centre of the applied load. This procedure was repeated in its entirety for different fulcrum settings.

The procedure to calculate the equivalent mass consisted of attaching circular markers to the springboard at different points from the board´s free end and determining the frequency of vibration using computer vision methods. The board was set into a state of free vibration by releasing it from a deflected position. The initial deflection was selected such that there was no separation between the board and the fulcrum during vibration. The initial deflection was selected such that there was no separation between the board and the fulcrum during vibration. This procedure was repeated at different board locations with the fulcrum set in different positions.

1.2. Dynamic Procedure to determine stiffness and effective mass

Other authors used a dynamic procedure to calculate a "dynamic" stiffness and equivalent mass simultaneously [6-7]. This procedure involves progressive loading of the board, setting the loaded board in motion, and measuring the period of board oscillation for each incremental load. According to Stone [5], the portion of board weight effectively oscillating is defined as the sprung weight (or effective mass, if expressed in kg).

$$T = 2\pi\sqrt{\frac{m_e + m_l}{k}} \quad (1)$$

$$m_e + m_l = \frac{kT^2}{4\pi^2} \quad (2)$$

$$m_l = \left(k(4\pi^2)\right)T^2 - m_e \quad (3)$$

Where, m_e represents the effective mass of the springboard in kilograms, m_l represents the applied load in kilograms, T represents the oscillation period in seconds and k represents the stiffness of the springboard in Nm^{-1}.

The period T for simple harmonic of a linear beam with stiffness k and effective mass m_e is given by *equation (1)*. For small oscillations where m_l is the mass of the load applied. This is rearranged to give *equation (3)*. A plot of m_l versus T^2 allows k.

Plotting *equation (3)*, the value of k (stiffness of the board) can be determined directly.

Stone [7] reported problems in obtaining spring constants using a static loading protocol. This procedure assumes no creep in board position during the loading sequence (a condition impossible to satisfy). Other investigators realized that when the fulcrum was set close to the board tip there were significant differences between statically and dynamically calculated stiffness (500-600 N/m). But, when the fulcrum was positioned near the middle and toward the back of its range, the parameters were very similar [2] [4] [5].

2. Methods

2.1. Motion capture of a springboard during a dive

A 4m x 4m x 4m volume at the tip of the 3 m springboards at Pond's Forge International Diving Pool in Sheffield was calibrated for 3D video reconstruction using two Phantom v4 high cameras [6].The method uses a chequerboard approach with the two synchronized cameras running at 500 frames per second and positioned at 90° to each other.

Each camera had a resolution of 512 x 512 pixels. Over 120 dives were recorded and subsequently analyzed from the 2009 FINA World Series in Sheffield in April 2009. Fig. 1. shows one such dive, with the vertical motion of the tip of the board during the dive shown in *Fig. 3.*

3. Results

3.1. Modeling the motion of the board

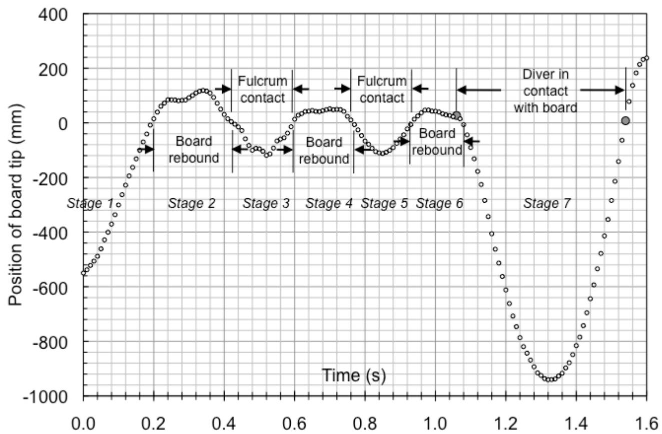


Fig. 1. Vertical motion of the board tip towards the end of the hurdle step indicating the different stages of motion of the board.

It can be seen that the dive consists of 7 stages:
1. The diver lands on the board during the 'hurdle' step;
2. The diver leaves the board which then rebounds from the fulcrum;
3. The board returns to the fulcrum and deflects under self-load;
4. The board rebounds from the fulcrum for a second time;
5. The board returns to the fulcrum for a second time and deflects under self-load;
6. The board rebounds from the fulcrum for a third time;
7. The diver lands on the board, it deflects to a maximum and the diver leaves on an upwards trajectory.

Fig. 1 also shows that, apart from the global vertical motion of the board, it also exhibits oscillations between 0.2 and 1.4 s. Thus, any model should include the deflections of the board, its modes of oscillations and interaction with the diver.

Following on from the hurdle step in stage 1, the board rebounds so that it is no longer in contact with the fulcrum (Fig. 2c). In the simplest model, it is considered that the board is rigid and rotates about the pin under the influence of gravity alone, producing a parabolic deflection the tip. The initial condition V_0 from stage 1 was determined experimentally from the displacement data and input to stage 2.

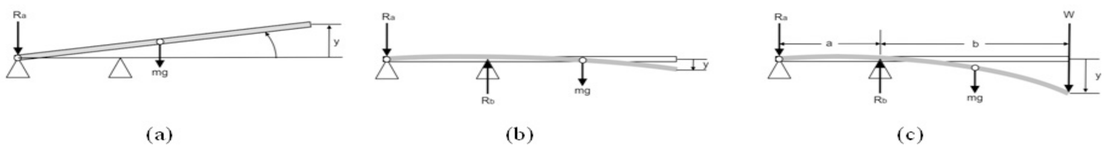


Fig. 2. Motion of a spring board during a forward dive with a hurdle step: (a) rebound of the board; (b) deflection when the diver is airborne; (c) deflection during diver contact.

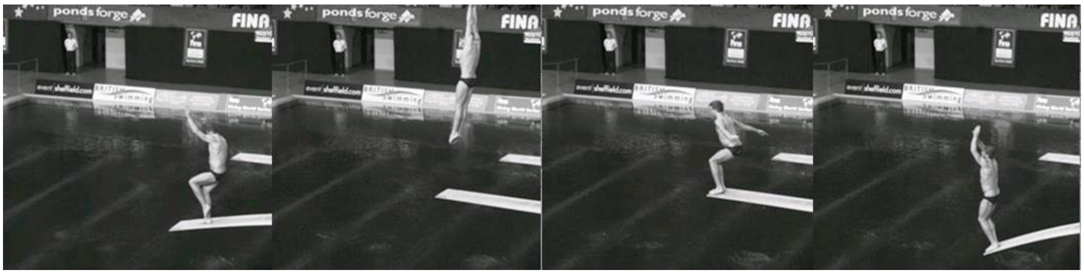
The board deflects downwards during two scenarios: (i) when the diver lands on the board; and (ii) when the board bounces on the fulcrum (Fig. 2). In both cases the deflection is considered to be due to a simple spring with stiffness *k*. Stages 1, 5 and 7 in Fig. 2 are symmetrical and sinusoidal, indicating that a force proportional displacement is appropriate. Stage 3 shows evidence of oscillations in the board and will be considered later. Thus, the deflection of the tip of the board is governed by:

$$y = Y_0 \sin(\omega t) \tag{4}$$

Where $\omega = \sqrt{k}/m$ and m is the mass of either the board or the board plus the diver depending upon the condition. Y_0 is the maximum deflection of the board given by $Y_0=V_0/\omega_0$ with V_0 provided by the output of the parabolic model in the previous section. The stiffness *k* was estimated by applying known weights to the tip of an identical board and measuring the deflection.

A frequency analysis of the deflection curve in Fig. 1 showed that the board oscillated at approximately 8.3 Hz when in contact with the fulcrum and 22 Hz when not in contact. It was thus assumed that the beam exhibited damped oscillations which were then added onto the spring-like deflection in the previous section. Fig. 1 shows one such dive, with the vertical motion of the tip of the board during the dive shown in Fig. 3.

Fig. 3. shows a diver conducting a 5353B manoeuvre, that is, 2.5 turns and 1.5 twists. The diver traverses down the springboard and initiates motion of the board with a hurdle step within 1m of its tip. The diver jumps and lands at the end of the tip as it oscillates beneath, causing it to deflect downwards around 1 m. As the board returns to its horizontal position the diver is launched upwards to execute – hopefully successfully – 2.5 turns and 1.5 twists. The success of the diver is generally considered to be a function of the final takeoff velocity of the diver and the ability of the diver to execute fast rotations. Success or failure, however, is very sensitive to the motion of the board immediately prior final contact. The board's motion is, in turn, a function of the position of the fulcrum, the stiffness of the board, and the excitation of the board initiated during the hurdle step.



Hurdle step | Max height of step | Initial contact | Max board deflection

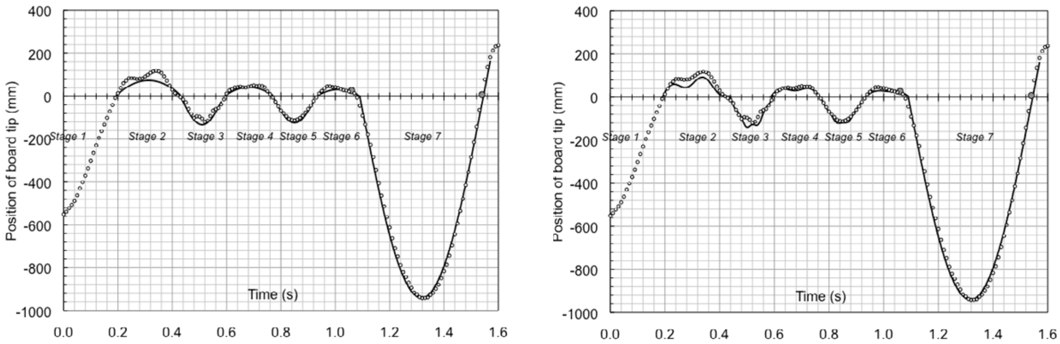
Final contact | Max dive height | 2nd Rotation | Final half rotation

Fig. 3. Clips from a reverse dive with 2.5 turns and 1.5 twists (5353B) taken with a Phantom v4 at 100 frames per second.

4. Discussion

The purpose of the modelling at this stage of the analysis is to identify the physics of the board's motion. The results in Fig. 4a shows that a relatively simple model can be used which assumes that the board is rigid and deflects as a simple spring. Fig. 4b shows that the addition of decaying oscillations after the hurdle step enhances the model. The model is very sensitive to input parameters for each stage such that poor estimates of V_0 at the beginning of stage 2 is carried through the successive stages of the model. It is intended that the input parameters at the very beginning of the dive will be measured either using video or sensors.

The model will be developed further to allow dives which don't include a hurdle step to be simulated since some dives begin with the diver in a static position on the tip of the board. Equally, a sensitivity analysis will be carried out to determine the effect of material parameters, the position of the fulcrum and the landing position of the diver.



(a) (b)

Fig. 4. Comparison of analytical models with experiment: (a) model without board vibrations; (b) model with board vibrations. Where continuous lines represents model data and dots represent experimental data.

5. Conclusion

This simple springboard model gives a good understanding about what is exactly happening during a dive. This knowledge might be useful to create a more sophisticated model and also to optimize the most important parameters to improve performance.

Comparison of the simplest model showed surprisingly good agreement with the experimental data, but with significant differences early on in the board's motion that were primarily due to board oscillation. Addition of damped harmonic motion at the natural frequencies seen in the experimental data (8.3 Hz and 22 Hz) allowed the simulation to follow the experimental data closely. The model will be developed to allow other dives to be simulated and to allow the optimization of the board stiffness and the position of the fulcrum for elite divers.

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