A device inspired by the mantis shrimp´s strike to produce cavitation bubbles on solid surfaces

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Abstract. We discuss a low-cost mechanical device designed to generate cavitation bubbles through the impact of rigid surfaces. The process is triggered by a pivoting limb, which develops speeds as high as 180 rad/s (9 m/s) while submerged in water. A mathematical model is proposed to describe the limb’s dynamics whose results are in good agreement with the experimental data. The model shows that more than 65 % of the elastic-potential energy to power the limb is dissipated by drag/friction effects. This key aspect must be considered when developing efficient devices for applications such as lithotripsy.

1. Introduction
The collision between solid surfaces in a liquid may generate high pressure gradients which induce nucleation of gas and vapor bubbles. Subsequently, these bubbles grow and collapse producing shock waves, microjets and short bursts of light, among other phenomena [1]. In particular, the jets may be powerful enough to rapidly erode and/or fracture solid surfaces due to the elevated stresses [2]. Both the phenomenon and its accompanying effects can be observed in nature. A notable example is the collision of the mantis shrimp’s appendage on a solid surface which, with an average duration of 49 µs, induces forces with magnitudes of 1,501 N and cavitation [3]. Interestingly, when these bubbles collapse near a solid surface, the forces involved may increase [3]. The powerful punch of the mantis’s appendage is characterized by speeds and accelerations of 4,500 rad/s and 10⁶ rad/s², respectively [4]. To develop this impressive kinematics, the crustacean has developed a complex mechanism with flexor and extensor muscles, latches, bars, and a hyperbolic paraboloid spring [4]. Some researchers have been inspired by the kinematic/dynamic performance of these animals, and thus have tried to emulate the energy storage and release mechanisms to mobilize artificial appendages [5]. In other studies, the interest has focused on the hydrodynamic generation of cavitation by means of impacting solids in liquid media [6]. In this work, two fundamental objectives are pursued: 1) to develop a bioinspired mechanical device to reproduce the powerful punch of the mantis shrimp, and 2) to produce cavitation during the collision of two rigid surfaces in water.
2. Apparatus
Figure 1 shows different views of the proposed apparatus. It consists of a pair of parallel walls that support a pivot around which a limb rotates. A set of rubber bands is attached to the bolts fixed to the parallel walls, while movable bolts are mounted on the limb. In the open position, the lower end of the limb is locked by a mechanical trigger and the rubber bands are fully stretched (figure 1a). When the trigger is activated, the rubber bands contract abruptly and the limb rotates in a clockwise sense, until it impacts the surface of a solid body (figure 1c).

![Figure 1](image_url)

*Figure 1* a) 3D CAD-model of the mechanical device to generate impact-induced cavitation (in open position); 1) pivoting limb, 2) impact washer, 3) parallel wall plates, 4) set of stretched rubber bands, 5) mechanical trigger, 6) corbel type supports, 7) curved sliding guides, 8) pivot, 9) solid rectangular prism, 10) flat solid surface, 11) set of band attachments, and 12) sliding bolts. b) Lateral view of the device to show how the angular displacement of the limb is measured. c) Device in closed position (washer is in contact with the solid surface); 13) contact point. d) Torques acting on the limb: $\tau_d$ is the driving torque, $\tau_v$ is the viscous friction torque, and $\tau_D$ represents the drag torque. The limb thickness is $e = 7$ mm and the length from the contact point to the pivot is $r = 49.3$ mm.
3. Experiments
The apparatus was set inside a rectangular tank, of size (44 × 44 × 22) cm³, filled with tap water. All experiments were conducted at room pressure and temperature (101,860 Pa and 23° C). A solid aluminum prism was set at the base of the tank, such that the washer at the end of the limb could hit its upper surface. The limb was released by the mechanical trigger and its motion was recorded with a SONY® RX100 V camera. The area of interest was illuminated with an 850 lumens lamp.

4. Limb’s dynamics
To determine the limb’s angular displacement \( \theta(t) \) we propose a simplified model based on the forces depicted in the free body diagram of figure 1d. Hence, in accordance with Newton’s second law (regarding the counter-clockwise direction as positive) it is readily found that:

\[
I_{xx} \frac{d^2 \theta}{dt^2} = -[K_1 \theta - K_1 \theta u(\theta - a) + (K_2 \theta + (K_1 - K_2)a)u(\theta - a)] + \lambda \left( \frac{d\theta}{dt} \right)^2 + \beta \frac{d\theta}{dt} \quad (1)
\]

Subject to the initial conditions:

\[
\theta(0) = \theta_0; \quad \theta'(0) = 0 \quad (2)
\]

The left-hand side of equation (1) is expressed in terms of the moment of inertia about the rotation axis \( I_{xx} \). The first term on the right-hand side describes the elastic driving torque produced by the set of rubber bands; \( u(\theta - a) \) represents the shifted unit step function, while \( K_1 \) and \( K_2 \) represent the stiffnesses defined by the slopes of the line segments depicted in figure 3d. It is worth noticing that the shape of this curve (i.e. denoting softening spring characteristics) is similar to those observed in force-deflection experiments with rubber bands [7]. The second term on the right corresponds to the fluid drag torque, which is proportional to the square of the angular velocity. The last term on the right-hand side of equation (1) accounts for the viscous friction caused by the motion of the fluid confined between the moving limb and the wall plates. In this last case, this respective force is assumed to be proportional to the angular velocity.

5. Results and discussion

5.1. Image sequence
Figure 2 shows a high-speed photographic sequence of the limb’s motion. It ranges from the fully open position, when the limb is mechanically released by the trigger, to the final close position when the impact washer hits the solid surface. During the collision, numerous cavitation bubbles form between the washer and the surface; these are pointed with an arrow in snapshot (9).

5.2. Comparisons between experiments and simulations
Figure 3 shows a comparison between the experimental data (obtained from image processing and video analysis using Tracker software) and the numerical integration of equation (1). Solid curves represent the best fit obtained via nonlinear least-squares method (implemented in Mathematica 10.0); the corresponding fitting parameters are: \( K_1 = 2.793 \text{ N} \cdot \text{m/rad} \), \( K_2 = 1.388 \text{ N} \cdot \text{m/rad} \), \( a = 0.359 \text{ rad} \), \( \lambda = 0.0000324 \text{ kg} \cdot \text{m}^2 \), \( \beta = 0.000799 \text{ kg} \cdot \text{m}^2/\text{s} \), \( \theta_0 = 0.999 \text{ rad} \). The moment of inertia, \( I_{xx} = 0.0000414 \text{ kg} \cdot \text{m}^2 \), was calculated by using the Solid Edge CAD-software. Since \( r = 49.3 \text{ mm} \) (see figure 2d) the estimated limb’s tangential speed and acceleration were \( 9 \text{ m/s} \) and \( 2,200 \text{ m/s}^2 \); these values are well below those achieved by specimens such as the peacock mantis shrimp (Odontodactylus scyllarus), respectively rated at \( 20 \text{ m/s} \) and \( 10^5 \text{ m/s}^2 \) [3]. It is worth mentioning that a simple way to get the kinematics of the device closer to that of the mantis shrimp is to increase the number of rubber bands (tension springs can even be used to supply the bands), thereby increasing the driving torque along with the speed and acceleration of the limb during this process.
Figure 2 High-speed photographic sequence of the limb’s motion, from its release time (snapshot 1), till its impact on the solid block (snapshot 9). Cavitation (indicated by a white arrow) is visible between the washer and the solid surface. The sampling frame rate was 959.04 fps.

Figure 3 Time evolution of a) the angular position of the limb (data are averages of three experiments with a standard deviation of 0.0349 rad), b) angular velocity ω, c) angular acceleration α, and d) driving torque versus rotational deflection. Symbols represent the experimental data and the solid lines were computed from equation (1). The total closure time of the limb is about 8 ms.
The area under the curve in figure 3d represents the energy available to drive the limb, which is approximately 1.1 J. Dividing this elastic-potential energy by the duration of the closing process, $t_c \approx 8$ ms, gives an average power of 137 W. On the other hand, the average kinetic energy delivered by the limb is estimated as $E_k = (1/2)I\omega^2 = 0.3$ J, where a mean angular velocity of $\omega = 121$ rad/s was taken in accordance to figure 3b. Therefore, the power used to accelerate the limb is about 38 W, representing only 28 % of the available power. The rest of the energy is dissipated by drag and friction torques. Figure 4 displays the available power curve (computed as $\theta'(t)\tau_c(t)$) as well as the drag ($\theta'(t)\tau_D(t)$) and friction ($\theta'(t)\tau_f(t)$) power loss curves. The horizontal dashed lines indicate the power average values for each curve as determined with

$$P_{avg} = \frac{1}{t_c} \int_0^{t_c} \theta'(t)T(t)dt, \quad (3)$$

where the function $T(t)$ is replaced by $\tau_c(t)$, $\tau_D(t)$ or $\tau_f(t)$ as appropriate.

According to figure 4, the power dissipated by both friction and drag effects is 92 W. The results of the previous energy analysis indicate the need for redesigning the device to achieve a more efficient use of the potential energy. Some improvements include modifying the front area of the limb to reduce the drag coefficient, reduce the limb length, use torsion springs working in the elastic range (this also greatly facilitates mathematical modeling).

![Figure 4](image.png)  
Figure 4: Power versus time curves associated with the potential energy stored by the rubber bands and with energy losses due to friction and drag. Horizontal lines indicate the average power.

Figure 5 shows that the maximum closing speed increase with the initial angle at which the limb is released. The relationship between these two variables is nonlinear (solid line) and is well predicted by equation (1). It is also important to note that the size of the cavitation bubbles increases with increasing the maximum closing speed (the photographs clearly show this). The inset plot shows the area of the cavitation bubbles (generated between the washer and the surface) as a function of the maximum closing speed; these two variables have a non-linear relationship as indicated by the dotted line corresponding to a polynomial fit ($Area = -0.412 - 0.276\omega_{max} - 3.87 \times 10^{-5}\omega_{max}^2$). It is worth mentioning that the area of the cavitation bubbles represents only the lateral projection of three-dimensional structures, the shape and size of which should be studied in detail.
Figure 5 Maximum angular velocity vs. angular position. Symbols are experimental data and the solid lines were computed with equation (1). The inset shows the area of the cavitation bubbles between the washer and the surface vs. the maximum angular velocity developed by the limb. Experiments “e1” and “e2” were performed without fully opening the limb, which was held and released manually.

6. Conclusions
We developed a simple bioinspired device to produce cavitation in the liquid layer entrapped between two approaching rigid surfaces. The experiments revealed the ability of the proposed design to produce cavitation bubbles during the collision process in water. In addition, a model was presented to describe the motion of the device limb in this environment. The numerical results are in good agreement with the experimental data. Future research will be focused on the development of applications in which the possibility of generating two impacts of similar intensity can be exploited simply by releasing the limb once. This could streamline the crushing process of solid minerals in medical treatments such as lithotripsy. This technique will shortly be applied to investigate the surface properties of certain materials under the localized action of high pressure and temperature spikes.

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