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1 Unveiling the physical mechanism behind pistol shrimp cavitation

2
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7 8 **Abstract**

9 Snapping shrimps use a special shaped claw to generate a cavitating high speed water jet. Cavitation
10 formed in this way, may be used for hunting/stunning prey and communication. The present work is a
11 novel computational effort to provide insight on the mechanisms of cavitation formation during the
12 claw closure. The geometry of the claw used here is a simplified claw model, based on prior
13 experimental work. Techniques, such as Immersed Boundary and Homogenous Equilibrium Model
14 (HEM), are employed to describe the claw motion and cavitating flow field respectively. The
15 simulation methodology has been validated against prior experimental work and is applied here for
16 claw closure at realistic conditions. Simulations show that during claw closure, a high velocity jet
17 forms, inducing vortex roll-up around it. If the closure speed is high enough, the intensity of the
18 swirling motion is enough to produce strong depressurization in the vortex core, leading to the
19 formation of a cavitation ring. The cavitation ring moves along the jet axis and, soon after its
20 formation, collapses and rebounds, producing high pressure pulses.

21
22 **Keywords:** Applied physics, Fluid dynamics, Information theory and computation.

23 24 **Introduction**

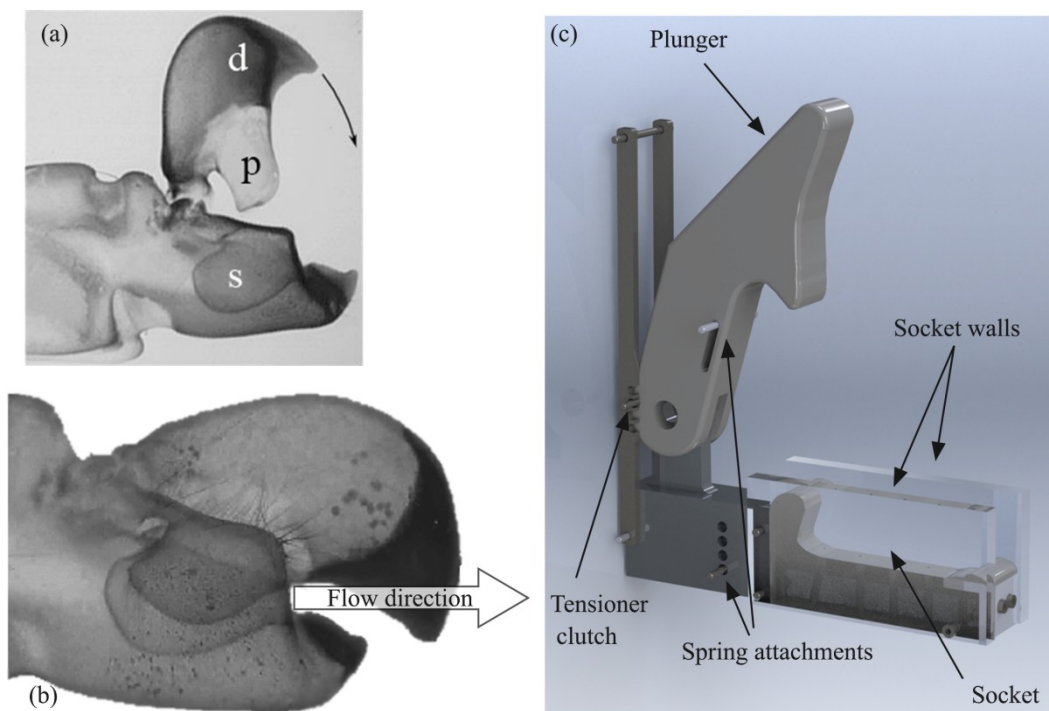
25 Cavitation in water/liquids is a very effective way of generating shock waves ¹, due to the rapid
26 accelerations/decelerations of the bubble interface during its collapse stage. Cavitation-related
27 phenomena may even appear in nature, in animal species; for example dolphins cannot swim faster
28 than 15m/s due to cavitation formation², which causes pain. On the other hand, the lack of pain
29 receptors on the fins of fish belonging to the scombrid family² (e.g. mackerels, tunas, etc.) allows
30 them to exceed the cavitation free-limit and cavitation-induced damage has been observed on their
31 bodies. Apart from the hindrance that cavitation may cause to swimming fish, other animal species
32 have evolved to exploit the generation of shock waves through cavitation to stun or kill prey.
33 Examples of such animals are snapping shrimps (belonging to the family of Alpheidae) and mantis
34 shrimps (belonging to the family of Odontodactylidae).

35 Mantis shrimps have two hammer-like or club-like raptorial appendages, which they use to strike
36 with extreme force their prey, such as e.g. small crustaceans or molluscs. High speed imaging
37 revealed that cavitation may form between the hammer-like appendage and the target^{3,4}. It is
38 speculated that the mechanism of cavitation formation is due to the strong depressurization of water
39 due to the Bernoulli principle³, i.e. as the fluid moves at high speed, its static pressure drops.
40 Moreover, it is likely that cavitation is enhanced by vortex formation and the hammer rebound after
41 the impact on the target surface³. However, there are indications that cavitation in the case of the
42 mantis shrimp may be an unwanted effect. Detailed inspection revealed that cavitation does not only
43 damage the target, but the mantis shrimp's appendages as well⁴. Over time, the appendage surface
44 becomes pitted and damaged, though frequent moulting of the mantis shrimp replaces the damaged
45 smashing surface. The aforementioned discussion indicates that perhaps in the case of mantis shrimp,
46 cavitation appears to be a side-effect of the percussion, with negative aspects that the shrimp has
47 evolved to handle. On the other hand, it seems that the pistol shrimp is the sole species evolved to

48 actively use cavitation itself as a weapon to kill/stun its prey. The mechanism of cavitation formation
49 in pistol shrimp claws will be analyzed in the present work, focusing on the fluid mechanics aspects
50 of its operation.

51 Snapping shrimps, known also as pistol shrimps, have two specially shaped claws, one of which is
52 enlarged and is capable of forming cavitation bubbles^{5,6}. Claws are expendable; if the large claw is
53 amputated, the smaller claw will grow to replace the missing limb, whereas a new minor claw will
54 grow in the place of the large claw⁷. The claw consists of two parts, the dactyl and the propus⁵. On
55 the dactyl there is a protrusion (it will be referred as plunger hereafter) which fits into a
56 complementary socket of the propus, see also Figure 1. When the claw is fully open, water fills the
57 socket of the propus. Then, when the claw closes rapidly, the plunger displaces water from the socket
58 volume. Water escapes through a narrow anterior groove formed between the plunger and the propus,
59 as shown in Figure 1. The water expelled from the socket through the groove, creates a vortex ring⁵ in
60 a similar way as an air vortex cannon⁸. Note that the shrimp claw is a complicated 3D shape and the
61 expelled jet is not aligned at the same plane as the rest of the claw, thus it is not obstructed by the
62 dactyl tip⁹. Hess et al.⁵ introduced the concept of formation number to explain the maximization of
63 momentum transfer from the jet to the vortex. The jet velocity has been estimated by Versluis et al.¹⁰
64 to be ~25 m/s, using high speed imaging of an actual pistol shrimp claw closing. Such a velocity may
65 lead to pressure drops of $\sim 3 \cdot 10^5$ Pa, which is enough to vaporise water locally¹⁰ forming a cavitation
66 bubble. Additionally, a simplified numerical investigation, based on the assumption of spherical
67 cavitation bubble solved with the Rayleigh-Plesset equation, indicated pressure levels during collapse
68 of even 2000 bar¹⁰. Furthermore, a study by Lohse et al.⁶ suggests that luminescence phenomena may
69 be observed at the collapsing bubbles formed by pistol shrimps.

70



71

72 Figure 1. (a) Snapping shrimp claw components: *d* corresponds to dactyl, *p* to plunger and *s* to socket⁵. (b) Closed claw; the
73 passage through which flow is expelled is visible⁵. (c) Render of the simplified claw geometry used in the present study and
74 in previous experimental investigations⁵.

75

76 While the aforementioned list of experimental work^{5,6,10} aimed to investigate the phenomena being
77 involved in the operation of the pistol shrimp claw, still the mechanism of cavitation formation is not

78 described and well understood. In particular, the work of Versluis et al.¹⁰ examined the macroscopic
79 cavitation formation from the claw and employed a simplified numerical model based on the
80 assumption of spherical bubble shape and relying on parameter fitting to explain cavitation formation.
81 In their work they recognised the lack of detailed flow field and pressure data in the vicinity of the
82 closing claw. The work of Lohse et al.⁶ discussed the light emission from collapsing bubbles
83 generated by pistol shrimps, hinting the extreme pressure/temperature conditions during collapse. Not
84 much explanation was provided on the cavitation mechanism or flow field though. Finally, the work
85 of Hess et al.⁵ was an experimental study aiming to describe the flow pattern during claw closure by
86 analyzing an enlarged dimensions claw, which was based on a real pistol shrimp claw, scanned using
87 X-ray Computational Tomography (CT). While vortex formation was demonstrated, the enlarged
88 dimensions of the claw geometry did not permit observations of cavitation.

89 The present work focuses on the fluid mechanics aspects of cavitation formation, growth and
90 collapse, by resolving the flow field around the claw using numerical simulations. The flow field is
91 something that was not analyzed in previous studies, due to experimental limitations. In particular,
92 investigations involving actual pistol shrimps, have constraints in shrimp handling, in the experiment
93 environment and conditions, thus inherently limiting the applicable measurement techniques. High
94 speed photography becomes problematic, since high frame rates are required (of the order of 10^6 fps),
95 lighting and focusing becomes difficult (the animal may move in a not very controllable manner). The
96 pressure signal recorded from the hydrophone may be excessively smoothed or underestimated by the
97 sensor bandwidth¹⁰. Moreover, the complexity of the geometry of the claw and the uniqueness of each
98 individual animal, hinder systematic and repeatable study. On the other hand, experimental replicas of
99 pistol shrimp claws lack in reproducing the conditions of cavitation formation; for cavitation to occur,
100 one needs a high speed moving object (the plunger). It is difficult to construct such a plunger in real
101 size dimensions, moving at real closure speed, plus there are difficulties in the experimental
102 techniques (similar to those mentioned above, i.e. high speed imaging, focusing/lighting etc.). This is
103 the reason why Hess et al.⁵ resorted to enlarged and non-cavitating conditions.

104 A general remark in both cases is that experimental techniques such as high speed photography, or
105 pressure signal measurements provide only partial views of the flow pattern and underlying
106 mechanisms. High speed photography can show the existence of cavitation only, but not the actual
107 density of the fluid. Hydrophones may provide information of the pressure signal at a given point, but
108 not everywhere. Particle-Image-Velocimetry (PIV) cannot provide insight in cavitating regions, since
109 the cavitation cloud obstructs the view. The advantage of a well-defined and converged simulation is
110 that it provides a well controlled environment for conducting studies, without limitations of measuring
111 techniques, since they are not necessary (no need for high-speed imaging, Particle-Image-
112 Velocimetry), the flow field is directly accessible in a quantitative manner everywhere. Also there are
113 much less limitations in the simulated conditions and geometry, ensuring repeatability and control.
114 With the above, it is not implied that simulation is the only viable method in conducting research; it is
115 clear that simulation may have pitfalls (hence the clarification "well-defined and converged"). It is
116 also clear that developing simulation tools requires experimentation and theoretical developments to
117 formulate modelling techniques and validate numerical results.

118 The present work in an attempt to demonstrate the fundamental flow effects occurring at the claw
119 of a pistol shrimp, the mechanism of cavitation generation, shape and collapse. The claw geometry
120 used is based on the simplified model of Hess et al.⁵. The reason for resorting to a simplified model is
121 mainly related to validation. There are experimental data available⁵ that can be used to test the
122 numerical methodology (see also *supplementary material 3 and 4*) and validate the predictive
123 capability of the model before further investigating cavitating conditions. Additionally, the simplified
124 geometry offers the possibility of repeatability in any further research; the geometry is provided as
125 supplementary material (see also *supplementary material 12*) in Parasolid Computer-Aided Design

126 (CAD) format that can be used by experimentalists to construct their own models, or researchers to
127 develop and test numerical techniques. Note that the methodology employed is applicable for any
128 arbitrary shape, should it be available in a clean Computer-Aided Design (CAD) format.

129 It is highlighted that in the frame of this work, instead of relying on modelled parameters/fitting, as
130 was the case in the work of Versluis et al.¹⁰, the whole claw and the surrounding fluid are simulated
131 with Computational Fluid Dynamics (CFD). Thus, the present work is the first to simulate the actual
132 flow field inside and outside the claw, demonstrating the flow physics, the cavitation structure and
133 providing additional insight in relation to experiments, since the inherent limitations of the latter are
134 avoided. Despite the simplifications in the claw geometry, the main mechanisms of cavitation
135 generation and collapse are replicable and similar magnitude of jet velocity is found as in experiments
136 involving real pistol shrimps. Briefly stated here, the claw closure produces a high speed jet. The high
137 speed jet induces vortex roll-up, which in turn leads to a strong pressure drop inside the core of the
138 vortex. If the jet velocity is high enough, a pressure drop of even $\sim 10^5$ Pa can be produced, which is
139 enough to vaporize water locally, forming a toroidal cavitation ring. The toroidal cavitation ring
140 oscillates, expanding and collapsing; at the instance of the ring collapse, very high pressures are
141 produced, due to the sudden deceleration of the surrounding liquid.

142 The simulation of vortex cavitating flows is rather challenging, since high resolution and low
143 numerical dissipation are required to accurately track the vortex¹¹. Additionally, cavitating flows are
144 rather difficult to describe and model, due to large pressure and density ratios; in the present
145 simulations, density varies from 998.2 kg/m^3 (pure liquid) to 0.017 kg/m^3 (pure vapour) and pressure
146 varies from ~ 2000 Pa (liquid/vapour mixture) up to $100 \cdot 10^5$ Pa (pressure peaks). These variations
147 have serious implications in the nature of the flow. Strong density variations imply prevalence of
148 compressibility effects, such as low speed shock waves in the bubbly mixture¹² and pressure pulses in
149 areas of cavitation collapse. Indeed, cavitating flows are known to have a vast variation in the speed
150 of sound, ranging from 0.01 m/s for liquid/vapour mixture up to 10^3 m/s for pure liquid^{13,14}.
151 Cavitation-related computational techniques involve fully Eulerian compressible techniques
152 (selectively¹⁵⁻¹⁷) or Eulerian-Lagrangian methods (selectively¹⁸⁻²⁰). Research on cavitation has many
153 practical applications, ranging from fuel injection systems^{21,22}, ship propellers²³ and pumps^{24,25} to
154 even drug delivery²⁶ and cancer treatment²⁷. The present research could further promote new and
155 efficient designs in water cleaning/purification devices^{28,29}, material processing and chemical
156 engineering³⁰.

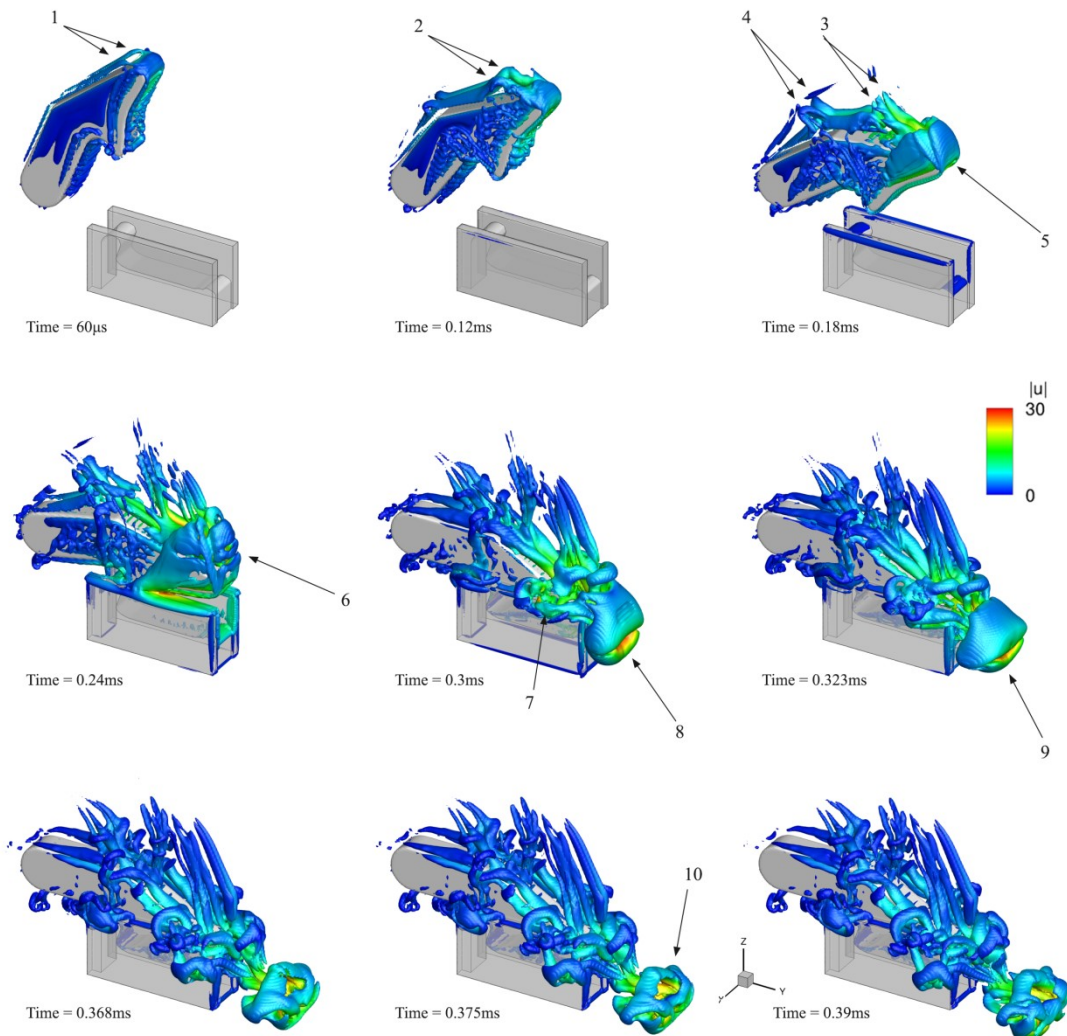
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158 **Results**

159 Several cases have been examined, for different plunger closure speeds and different plunger sizes.
160 Here, the focus will be on the results of a case with strong cavitation formation to demonstrate the
161 underlying physical mechanisms. The interested reader is addressed to the supplementary material for
162 a complete reference on all cases. The configuration to be presented features a socket with a
163 characteristic length scale of $\sim 1.4 \text{ mm}$ and a plunger closure speed of 0.3 ms , resulting to a peak
164 plunger angular velocity of $\sim 7000 \text{ rad/s}$. The Reynolds number of the jet diameter is $Re_D \sim 4000$ or,
165 based on the plunger length scale, $Re_L \sim 40000$.

166 The developing vortices during the plunger closure are shown in Figure 2 and a close-up view
167 around the jet in Figure 3. Vortical structures are indicated with the isosurface of the q -criterion
168 (defined as the second invariant of the velocity gradient tensor^{31,32}) for a value of 10^8 s^{-2} . As the
169 plunger starts to move, flow detachment occurs and two counter-rotating vortices form at the wake of
170 the plunger, indicated with (1). As the plunger continues to move, these vortices become larger and
171 start to twist, see (2), (3) and (4). The tip of the plunger is covered by a stretched vortical structure,
172 see (5), occupied by vapour at its core (see also Figure 4 at the same time instant). Later on, vortex
173 instability³³⁻³⁶ leads to break-up of the aforementioned structures, see the wake of the plunger at

174 0.24ms or at (6), where the originally stretched vortical structure breaks to several smaller structures.
 175 At the same time instant, an attached vortex grows at the wall edge of the socket, due to fluid being
 176 expelled from the socket cavity. Because of the closure speed, a high speed jet is expelled from the
 177 opening between the plunger and socket walls. The jet velocity is ~ 30 m/s, inducing vortex roll-up
 178 and causing the formation of a large vortex ring, as shown at (8) at 0.3ms, occupied by vapour due to
 179 strong circulation, see (4) at Figure 4. Vortex roll-up is also observed at the sides of the socket walls,
 180 due to liquid escaping from the gap between socket walls and plunger, see (7). After its formation, the
 181 vortex ring detaches from the socket/plunger opening and starts to move in the direction of the jet, at a
 182 translation velocity approximately half of the jet velocity. The same mechanism is in agreement with
 183 experimental observations, see ^{5,37}. Soon after its formation, the vortex ring elongates, see (9) at
 184 0.323ms, and then breaks into a complicated vortical structure, see e.g. (10) at 0.375ms, due to vortex
 185 instability, the collapse and rebound of the cavitation ring.



186
 187 Figure 2. Indicative instances of the 'real size' claw model closure; closure time 0.3 ms. Vortices are shown, represented with
 188 the velocity gradient second invariant (value $q=10^8$ s⁻²), coloured according to the velocity magnitude.
 189

190 The formation of the vortex ring is shown in detail in Figure 3. Initially, at 0.252ms, an attached
 191 vortex starts to form at the edges of the geometry, due to the expelled water jet. Note that the
 192 rectangular shape of the geometry causes the formation of a rectangular vortex ring as well. Later on,
 193 at 0.276ms, the vortex ring continues to grow and detaches. Its shape still resembles a rectangle,
 194 though it is smoothed at corners under the influence of viscosity. At 0.315ms the vortex ring has
 195 completely detached and travels following the jet. Its shape is elongated in the x-direction, resembling

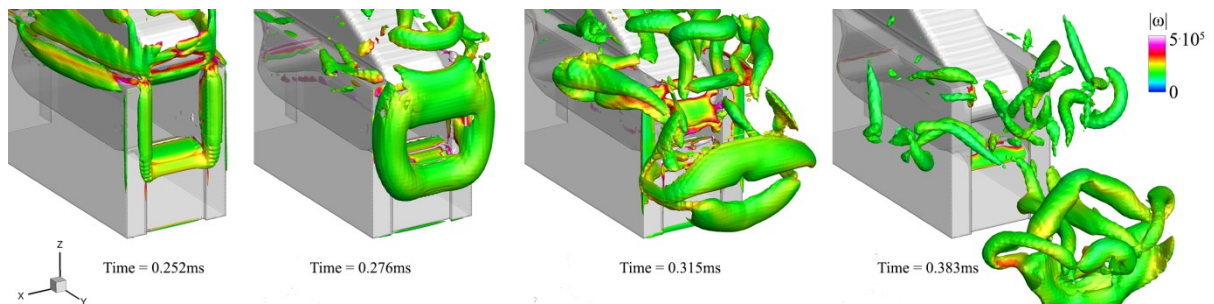
196 two cylinders with a gap in between, through which the jet moves. The elongated jet shape is caused
 197 by the asymmetric flow field promoted by the plunger motion. Finally, at 0.383ms, the vortex ring
 198 appears shattered after the cavitation ring collapse.

199 Colouring in Figure 3 provides an indication of the swirling motion that the fluid is subjected to.
 200 The colouring is according to the vorticity magnitude, $|\omega|$ (defined as the magnitude of the curl of
 201 velocity vector field³⁵). Under the assumption of forced (or rigid body) vortex type, vorticity and
 202 angular velocity are linked. Vorticity is twice the angular velocity of the instantaneous principal axes
 203 of the strain-rate tensor of a fluid element³⁵. This implies that the liquid is undergoing intense
 204 swirling, since angular velocities may range from $\Omega \sim 80000 - 170000$ rad/s. The induced liquid
 205 depressurization (defined as pressure at vortex radius R , p_R , minus the pressure at the vortex core, p_c)
 206 may be expressed as¹³:

$$207 \quad p_R - p_c = \frac{\rho R^2 \Omega^2}{2} \quad (1)$$

208 Considering that the liquid density is $\rho \sim 998.2$ kg/m³ and the vortex radius is $R \sim 0.1-0.3$ mm,
 209 then the pressure drop ranges between $\sim 5 \cdot 10^4$ up to even 10^6 Pa, with an average pressure drop of
 210 $\sim 2 \cdot 10^5$ Pa. This value is similar to the one used as a fitting parameter by Versluis et al¹⁰, justifying that
 211 despite the simplicity of the model geometry, there is similarity in the underlying physical
 212 mechanisms of actual shrimp claws. It should be noted that the forced vortex assumption is not
 213 necessarily far from reality, since real fluid vortices are combinations of forced and free vortices.
 214 Moreover, this assumption serves to provide an order of magnitude estimate of the angular velocity,
 215 explaining the induced liquid depressurization.

216



217
 218 Figure 3. Indicative instances of the vortex ring formation, vortical structures indicated using a q-criterion value of $5 \cdot 10^9$ s⁻².
 219 The isosurface is coloured according to local vorticity magnitude, providing an indication of the swirling angular velocity.

220 Note that due to the square opening between plunger and socket, the vortex ring has initially a square shape as well.

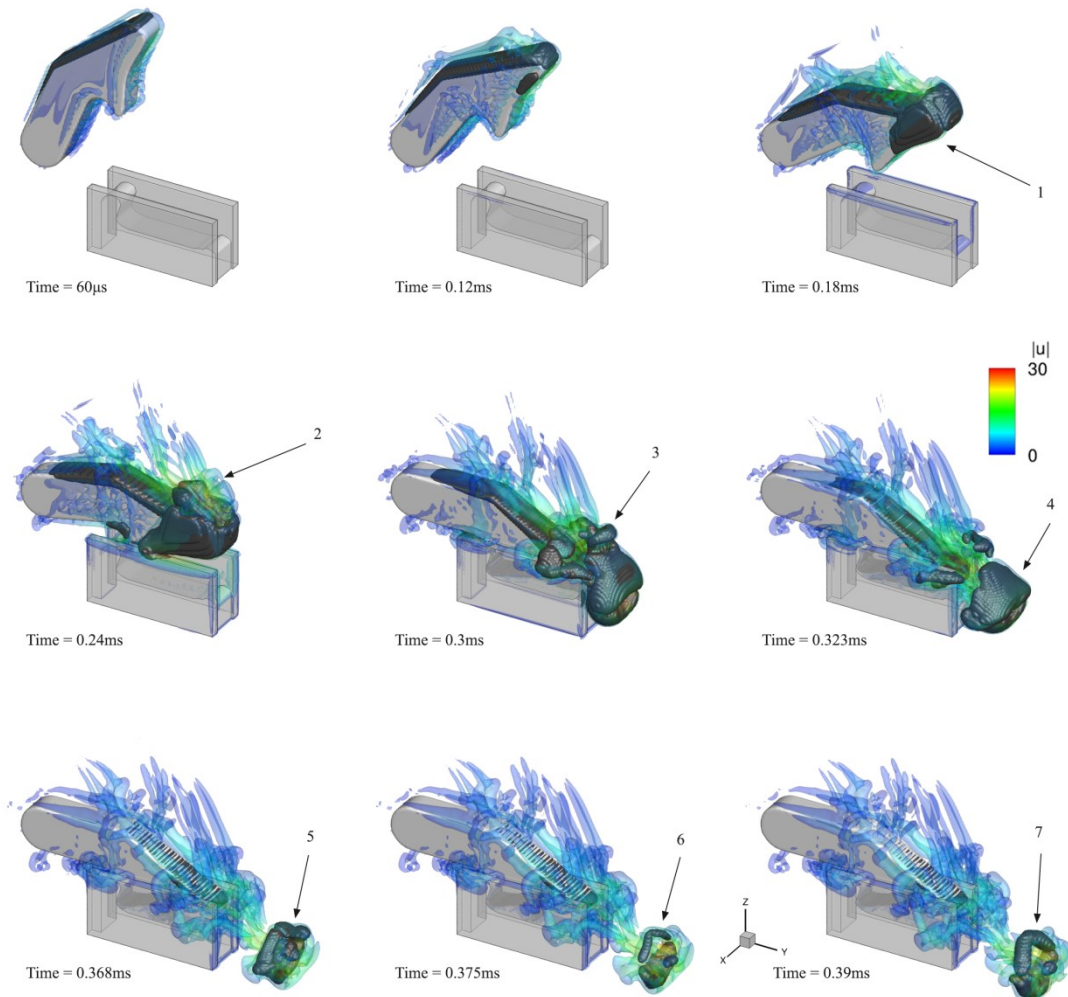
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222

223 In Figure 4, indicative instances of cavitation formation are shown, combined with the presence of
 224 turbulent structures. Turbulent structures are represented as translucent isosurface, whereas cavitation
 225 is represented using the density isosurface, for a density value of 990 kg/m^3 (or vapour volume
 226 fraction of $\sim 1\%$). This combined representation enables to link cavitation structures with vortical
 227 structures. At the start of the plunger motion, attached cavitation develops at the wake of the plunger
 228 due to local flow detachment. As the plunger accelerates, reaching maximum angular velocity, flow
 229 detachment at the sides and the tip of the plunger induces the formation of cavitation sheets, see (1) at
 230 0.18ms. Later on, detached cavitation structures are observed at the plunger wake at the cores of
 231 vortices, e.g. see (2) and (3). The rapid plunger closure leads to the formation of a cavitating vortex
 232 ring around the high speed jet, which is clearly shown in (4). After formation, the cavitation vortex
 233 ring moves following the jet and oscillates, collapsing and then rebounding again, see the sequence of
 234 (5 - collapse), (6 - minimum size) and (7 - rebound). At minimum ring minor radius, at the final stage
 235 of collapse and before the cavitation ring rebound, very high pressures are generated, in the order of

236 100 bar. At the same time, the strong flow acceleration, due to vortex rebound deforms the vortex
 237 even more and shatters the cavitation ring.

238 The generated vortex ring cross-section is a Burgers vortex and its circulation is $\sim 0.005 \text{ m}^2/\text{s}$
 239 throughout the whole simulation time. The minor radius of the forced vortex core is $\sim 0.11 \text{ mm}$ at
 240 generation, later increasing to 0.22 mm after the cavitation ring rebound.
 241



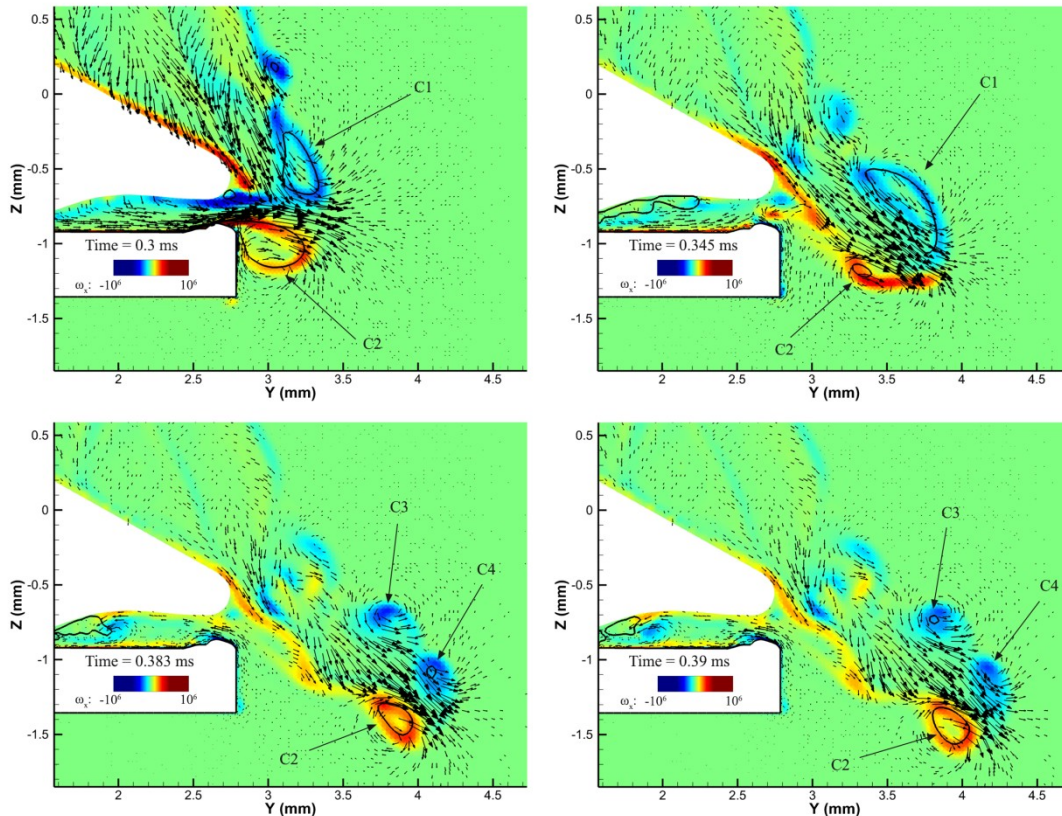
242 Figure 4. Indicative instances of the simplified claw model closure; closure time 0.3 ms. Vortices are shown, represented
 243 with the velocity gradient second invariant (value $q=10^8 \text{ s}^{-2}$), coloured according to the velocity magnitude (semi-transparent
 244 isosurface). Cavitation is shown with a density isosurface for a value of 990 kg/m^3 (i.e. vapour vol. fraction $\sim 1\%$ - black
 245 opaque isosurface).
 246
 247

248 To demonstrate with clarity the flow field, Figure 5 shows the flow field at the midplane of the 3D
 249 geometry. Flow velocity is represented with velocity vectors whereas the contour shows vorticity at
 250 the normal, to the midplane, direction (ω_x). Cavitation is represented using a density isoline for a
 251 value of 500 kg/m^3 (or 50% vapour volume fraction). The core of the vortex ring is tracked over time
 252 and annotated with arrows.

253 Instances in Figure 5 show clearly the correlation of vortex roll-up with cavitation structures; note
 254 that at 0.3ms (plunger closure) cavitation occupies entirely the core of the two counter-rotating
 255 vortices, indicating as "C1" and "C2". At 0.345ms, "C1" becomes larger, whereas "C2" shrinks, due to
 256 the interaction of jet and plunger wake. After the collapse of the cavitation ring, "C1" vortex splits in

257 two. The two new vortices, named "C3" and "C4", may cavitate alternatively, e.g. at 0.383ms vortex
 258 "C4" cavitates, whereas at 0.39ms vortex "C3" cavitates.

259 Plunger motion displaces liquid from the socket, causing the formation of a high speed jet towards
 260 the +y direction. However, the plunger imparts momentum to liquid at its wake, towards the -z
 261 direction. Interaction of the jet with fluid from the plunger wake leads to a deviation of jet and
 262 cavitation vortex ring from the horizontal direction. Indeed, the jet-wake interaction imparts
 263 downward momentum to the jet, which is observable in the presented instances in Figure 5. Similar
 264 effect was observed in the experiment as well and it is demonstrated in the validation study in the
 265 supplementary material.



266
 267 Figure 5. x -vorticity (ω_x , 1/s) and velocity vectors represented at the midplane (yz -plane) of the geometry. The black thick
 268 line indicates a density isoline of 500 kg/m^3 (i.e. vapour volume fraction of 50%).
 269

270 Discussion

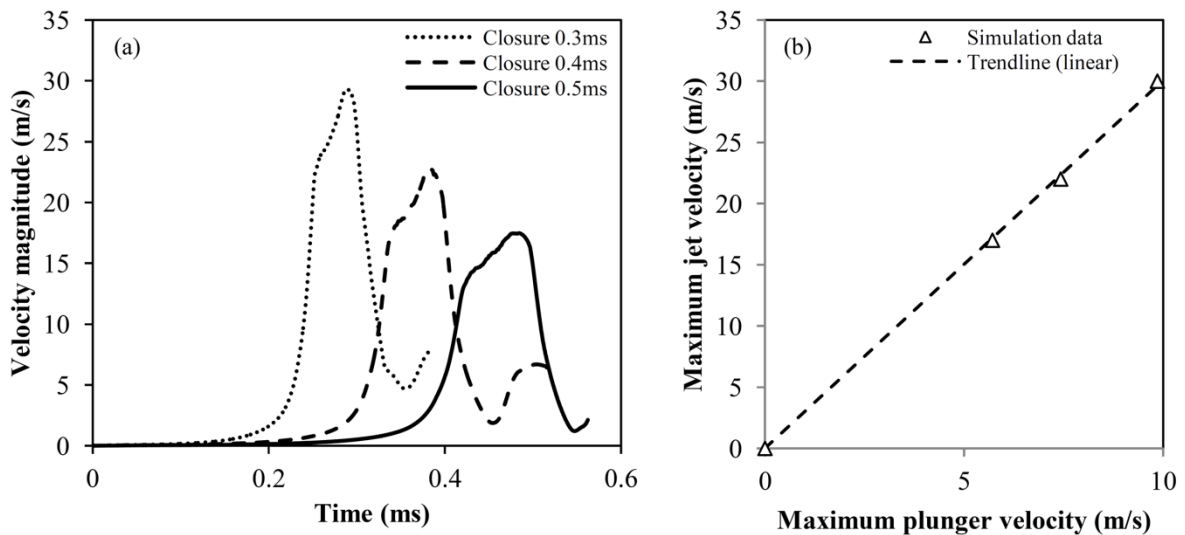
271 Even though cavitation ring rebounding might seem unexpected, the rebound mechanism is
 272 physical and is related to conservation of angular momentum. Indeed, it may be proven that, for a
 273 vortex (cylindrical or toroidal), circulation acts in a similar way to a non-linear spring, preventing
 274 complete collapse, since the induced centrifugal forces tend to increase the vortex size, eventually
 275 leading to rebound, see J.P. Franc¹³. In essence, as long as vorticity is preserved (e.g. inviscid fluid),
 276 the cavitation ring would rebound indefinitely. The collapse time for a toroidal cavitation ring may be
 277 approximated as¹³:

$$278 \quad \tau \cong R_0 \sqrt{\frac{\rho}{\Delta p}} \sqrt{\ln \frac{8}{\varepsilon}} \quad (2)$$

279 in the limit of small minor to major torus radius ratio. In equation (2), R_0 is the minor torus radius, ρ is
 280 the liquid density, Δp is the pressure difference between far field and the cavitating vortex core and ε
 281 is the ratio between the minor and major torus radii. For the configurations examined in the present

282 work, the R_0 is ~ 0.1 mm, $\Delta p \sim 97$ kPa, $\rho \sim 998.2$ kg/m³ and $\varepsilon \sim 0.16$, leading to an oscillation period
 283 approximately twice the collapse time, i.e. $\sim 32\mu$ s.

284 Since in nature pistol shrimps are not identical, it is reasonable to expect variations in the claw size
 285 or closure speed. For this reason, a parametric investigation was performed to determine the effect of
 286 the closure speed to jet velocity and cavitation volume. In Figure 6a, a comparison between the jet
 287 velocity of several cases is shown, for claw closure times of 0.3 ms, 0.4 ms and 0.5 ms. The angular
 288 closure speeds range between 4000 up to 7000 rad/s and plunger velocity at tip between 5.7 up to
 289 10m/s. Jet velocity is measured at the neck of the formed orifice, as in the experiment⁵. The peak jet
 290 velocity is a linear function of the maximum plunger closure velocity (see Figure 6b). In all cases a
 291 local minimum is found after the jet velocity peak, which is closely followed by a second peak, much
 292 smaller than the first. This second peak is associated with flow reversal inside the socket. Indeed,
 293 during the last stages of the plunger closure, depressurization induced cavitation occurs between the
 294 socket/plunger, due to the expelled jet inertia. Thus, shortly after the jet formation, flow rushes back
 295 at the cavity formed between the plunger/socket. Indicative instances of the flow reversal are shown
 296 in supplementary material.

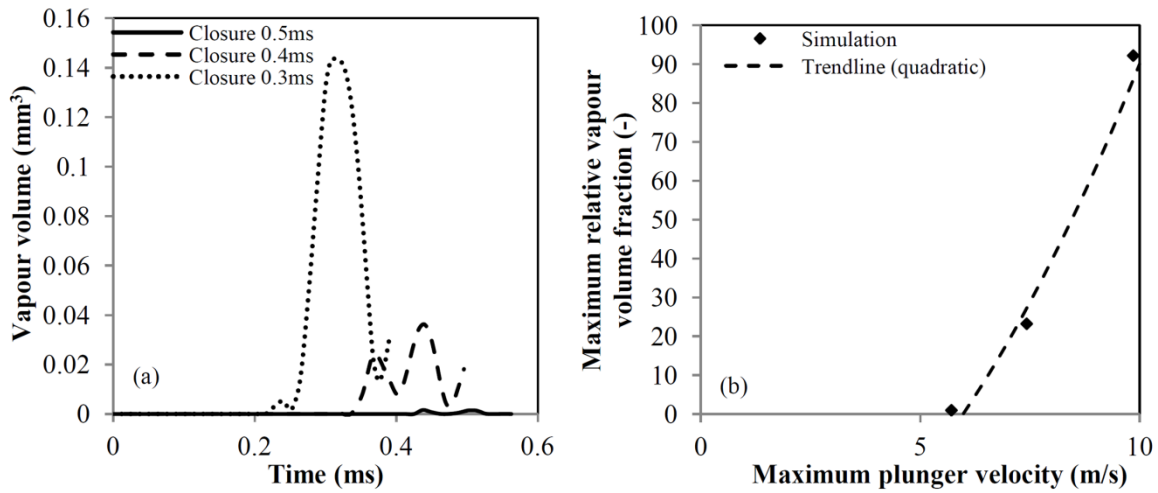


297
 298 Figure 6. (a) Comparison of the flow velocity at the neck, for different closure speeds. (b) Relation between the maximum jet
 299 velocity and the maximum plunger velocity.
 300

301 Figure 7 shows the vapour volume in the cavitation ring formed by the plunger closure in respect
 302 to time. A global maximum of vapour volume is clearly observed around the time of plunger closure,
 303 closely followed by a local minimum due to the cavitation ring rebound. The time scale of the ring
 304 rebound is $\sim 70\mu$ s, close to the calculated period from equation (2). Discrepancy is expected, mainly
 305 because equation (2) is applicable for small minor to major torus radius ratio and a perfectly circular
 306 ring, which is obviously not the case here.

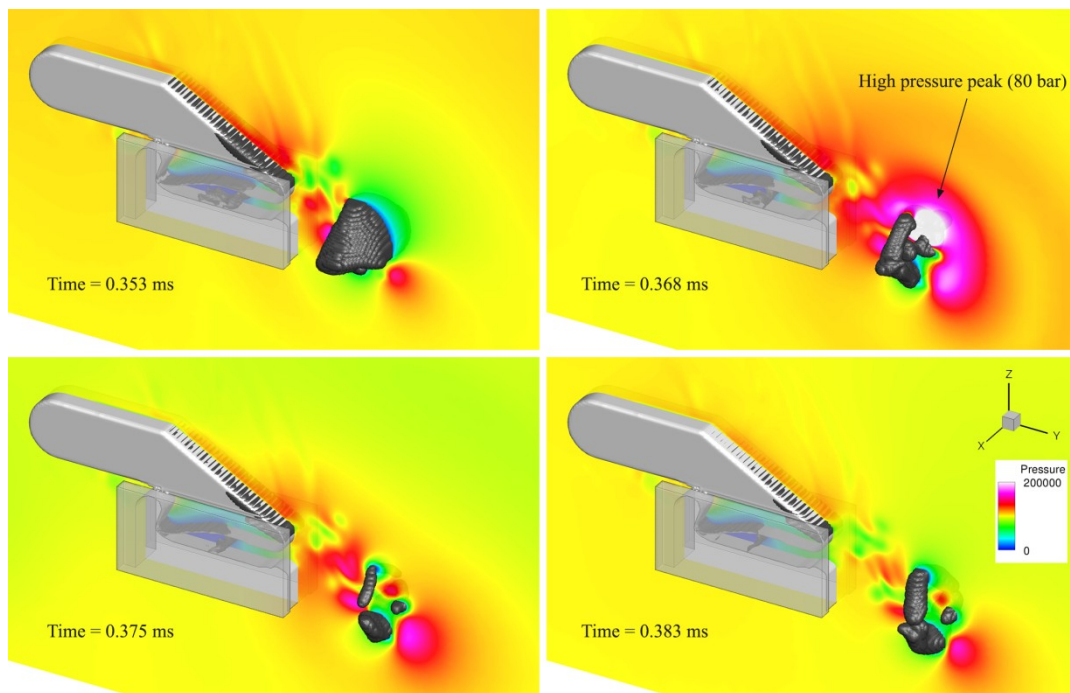
307 The maximum volume of vapour is related to the closure speed as a quadratic function of the form
 308 $V(u) = au^2 + b$, see Figure 7b. This form resembles the dynamic pressure contribution ($0.5\rho u^2$),
 309 including a constant value which is related to the vaporization pressure threshold. As already
 310 demonstrated, the plunger speed is linearly related to the jet speed. The jet speed affects the pressure
 311 inside the vortex core, since vortex pressure is a quadratic function of tangential vortex velocity¹³. It
 312 is highlighted that Figure 7 discusses only cavitation volume in the ring, omitting cavitation formed at
 313 the wake of the plunger or inside the socket, since the latter may not be relevant to the actual shrimp
 314 claw, due to differences in the exact claw shape. In any case, for the sake of completeness, it is

315 mentioned that the trend relating maximum vapour volume in the whole computational domain to the
 316 closure speed is similar to the one shown in Figure 7b.



317
 318 Figure 7. (a) Comparison of the vapour volume generated during the plunger motion. Calculation performed as the volume
 319 integral of the vapour volume fraction. (b) Maximum relative vapour volume defined in respect to the slowest closure speed
 320 investigated (i.e. 0.5ms closure, total vapour volume of 0.00156 mm³).
 321

322 As the cavitation ring collapses and rebounds, very high pressures are produced due to sharp
 323 deceleration of surrounding liquid. In essence, the sudden deceleration of liquid results to a water-
 324 hammer effect, consequently emitting a pressure pulse. This pressure pulse is the speculated
 325 mechanism employed by the pistol shrimp to stun or kill its prey¹⁰. The generated pressure peak is
 326 closely related to the amount of vapour produced during the plunger closure. When the plunger moves
 327 at the highest speed examined here (closure at 0.3ms, max. angular velocity 7000 rad/s, see *Results*
 328 section), an intense pressure peak is found, reaching instantaneous pressures of even 80bar, see Figure
 329 8.

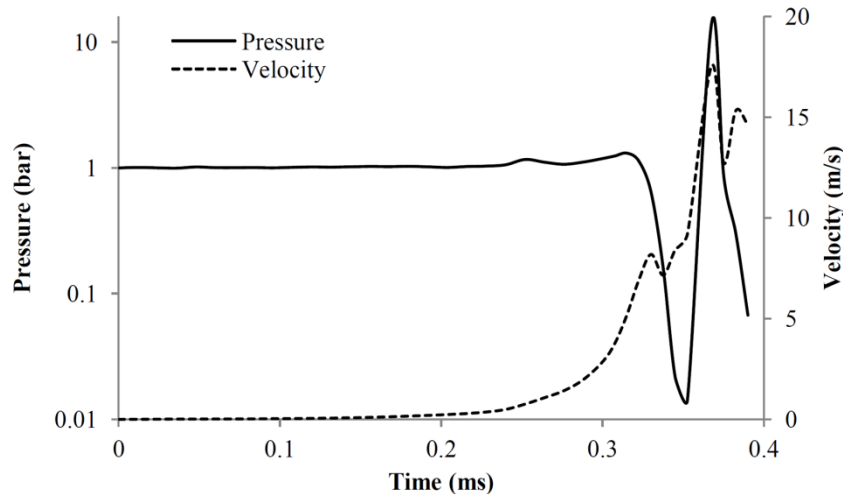


330
 331 Figure 8. Pressure peak due to cavity collapse, plunger closure at 0.3ms. Pressure is shown at a midplane slice. The black
 332 isosurface is the 1% vapour fraction. Pressure, locally, may exceed 80bar.

333

334 Figure 9 shows the time evolution of pressure and velocity magnitude at a characteristic length
335 scale $L \sim 1.4$ mm (see table 1) away from the claw neck, at the y -direction, for plunger closure at
336 0.3ms. Before the time of 0.2 ms, pressure signal is almost stable. Then, from 0.2 to 0.3 ms small
337 pressure peaks are detected, followed by a sudden pressure drop at 0.35 ms. At the instance of
338 cavitation ring collapse a very high pressure pulse is found, reaching pressures of more than 10 bar.
339 At the same time instant there is a local maximum of flow velocity, reaching 17m/s. The pressure
340 peak is then followed by a second pressure drop. The pressure signal pattern is the same as the one
341 found in the prior work by Versluis¹⁰.

342



343

344 Figure 9. Pressure and velocity magnitude as a function of time, at a characteristic length scale $L=1.4$ mm from the claw
345 neck.

346

347

348 To summarize, the present work is the first to analyze the cavitating flow in a geometry resembling
349 a pistol shrimp claw, providing insight in the physical mechanisms of cavitation generation and
350 proving that cavitation produced by the shrimp claw is not a spherical bubble but rather a toroidal
351 cavitation structure. The main mechanism of the cavitating claw operation is vortex ring roll-up,
352 induced by the high speed jet expelled from the socket. Depending on the plunger closure speed,
353 circulation of the vortex ring may become high enough to cause a considerable pressure drop inside
354 the vortex core. A large pressure drop may induce vaporization of the liquid inside the vortex core,
355 leading to the formation of a cavitating vortex ring. Upon its formation, the cavitation ring travels at
356 the direction of the jet, with a translational velocity around half of that of the jet and its minor radius
357 oscillating until viscosity dissipates angular momentum. The oscillation of the cavitation ring leads to
358 periodic collapses and rebounds, which emit high pressure pulses. These pressure pulses are used by
359 the shrimp for communication, as a defence mechanism, to stun, or kill the shrimp's prey.

359

360 Considering all the aforementioned observations, similarities and differences of the flow produced
361 by a simplified and an actual pistol shrimp claw may be summarised. First of all, from the results it is
362 clear that, as the claw plunger moves inside the socket, the displaced liquid forms a high velocity jet,
363 which in turn induces vortex ring roll-up. The shape of the vortex ring will affect the shape of
364 cavitation in the vortex core. While in the simulation the vortex ring is rectangular, due to the square
365 shape of the plunger-socket opening, in reality the shrimp's claw opening is a smooth curve leading to
366 a more circular vortex ring. In the simulation, cavitation at the wake of the plunger was observed. In
367 reality, the streamlined shape of the claw means that flow detachment is limited, thus there is very
368 little cavitation, if any. Moreover, whereas in simulation the socket was fixed in place, in actual pistol
shrimp claws both plunger and socket move at opposite directions, offsetting somewhat the jet

369 deviation introduced by the plunger wake. Despite these differences, quantitative characteristics of
370 claw operation have been reproduced. In particular, the maximum plunger angular closure speed in
371 the simulation was 7000rad/s, whereas actual claws¹⁰ close at comparable speeds of 3500rad/s.
372 Plunger closure results to water jet speed of 28-31m/s predicted by the simulation, whereas
373 measurements¹⁰ in real claws indicate jet velocities of 25-32m/s. The pressure drop predicted by the
374 intense swirling motion of the liquid is very similar to the one imposed as fitting parameter by
375 Versluis et al.¹⁰ (simulation $\sim 2 \cdot 10^5$ Pa, reference $2.2 \cdot 10^5$). Moreover, the peak pressure measured from
376 the bubble collapse is comparable to the one found from the present study, see P. Krehl¹, and the
377 pressure signature is very similar to that measured by Versluis et al.¹⁰. It is also highlighted here, that
378 effects found in the simulations may be confirmed by early investigations of other researchers,
379 working on similar simplified claw models under cavitating conditions, see the work of Eliasson et al.
380^{38,39}. To be more specific, the downwards deflection of the jet and the cavitation ring, the formation of
381 cavitation at the wake of the plunger and the formation of cavitation inside the plunger/socket cavity
382 are clearly shown in high speed videos^{38,40}, providing additional validation of the presented results.

383

384 **Methods**

385 The numerical methodology used in the present work is discussed in detail in the supplementary
386 material, but will be described here briefly. The plunger motion is imposed using an Immersed
387 Boundary (IB) technique⁴¹⁻⁴³. The advantage of this technique is that the computational domain
388 remains unchanged throughout the whole simulation time, thus greatly simplifying geometry
389 manipulation, especially in cases of small gaps or contact regions. Cavitation is modelled using the
390 Homogenous Equilibrium Assumption^{15,44-46}, thus pressure and density are directly linked through an
391 Equation of State (EoS) describing the phase change process. This assumption is justified based on
392 cavitation tunnel experiments⁴⁷.

393 The geometry used for the simulations is based on prior experimental studies⁵. Experiments were
394 based on the claw morphology of a typical specimen of snapping shrimp, *A. bellulus*. The
395 morphology of the claw was obtained in a computerized form using X-ray micro-Computed
396 Tomography (μ -CT) scanning, at fully closed and open positions. A two dimensional slice was
397 extracted along the midplane of the claw geometry, obtaining the mean profile of plunger and socket
398 geometry. This two dimensional slice was extruded in the 3rd direction, to obtain a simplified model
399 of the shrimp claw. Additionally, scale similarity was exploited to manufacture an enlarged scale
400 model of the claw (scale 70:1), which has been used for experimental studies, involving flow
401 visualization and Particle Image Velocimetry. In the scope of the present study, two types of
402 simulations have been performed. One simulation involved the 'enlarged model' geometry that was
403 used in previous experiments, at the same conditions (e.g. plunger closure profile). The aim of this
404 simulation was to validate the numerical framework and detailed results are presented in the
405 supplementary material. The second set of simulations involved parametric studies of the 'real size'
406 geometry, based on the dimensions of the actual snapping shrimp claw. Results of the second set of
407 simulations are presented in this paper, since they involve cavitation related effects which are the
408 focus of the study.

409 As shown in Figure 10a, the experimental geometry has many construction features, such as holes
410 for spring attachments, hinge shaft etc. Such features are not necessary for the simulation, since the
411 area of interest is in the flow channel between plunger and socket. Thus, such features have been
412 removed (Figure 10b). Moreover, the fillet of the geometry has been removed (Figure 10c), for
413 simplifying the triangulation of the plunger surface, which is needed for preparing the marker point
414 set (see supplementary material 1). The plunger initially is positioned at 73° from the fully closed
415 configuration.

416

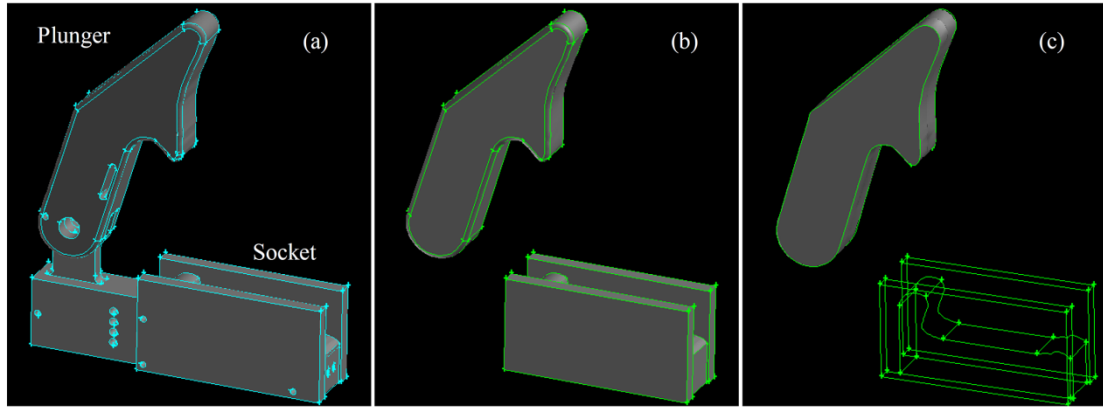


Figure 10. Left to right: (a) original geometry, used for enlarged scale experiments, (b) simplified geometry (hole and small features removed) and (c) final geometry (fillets removed). In (c) the wireframe of the socket is shown, providing a view to the inner geometry of the socket.

The simplified pistol shrimp claw dimensions, jet velocity and Reynolds number are outlined in Table 1.

Table 1. Characteristics of the real size and enlarged models examined⁵.

	Experiment - 'enlarged model'	'Real size'
Geometry - L (socket length scale)	0.1 m	1.41 mm
Liquid dynamic viscosity - μ	5 mPa.s	1 mPa.s
Density - ρ	998.2 kg/m ³	998.2 kg/m ³
Closure time - $t_{closure}$	0.5 s	0.5 ms
Indicative Velocity - u	~ 1 m/s	~ 17 m/s
Reynolds number - Re_L	~ 20000	~ 20000

The Reynolds number may be defined based on the socket length scale, L , as in the experiment⁵ for consistency:

$$Re_L = \frac{u \cdot L \cdot \rho}{\mu} \quad (3)$$

It is highlighted though, that the velocities reported in Table 1 occur in the neck region of the formed nozzle, as the claw closes. Thus, one could define the Reynolds number, based on the jet diameter, D , which is comparable to the nozzle neck, i.e. ~ 1 cm for the 'enlarged model' or ~ 0.14 mm for the 'real size' model, as:

$$Re_D = \frac{u \cdot D_{jet} \cdot \rho}{\mu} \quad (4)$$

Based on the nozzle dimensions, the jet Reynolds number is $Re_D \sim 2000$ for both 'real size' and 'enlarged model' cases. The maximum jet Reynolds number of the parametric cases examined is ~ 4000 , thus the developed flow is laminar or at the borderline to transitional, consequently an explicit turbulence model was not used.

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568 Data collection, CAD model preparation. M. Gavaises, Concept and design, financial support. All
569 authors have read and revised the manuscript.

570

571 **Competing Interests**

572 The authors declare that they have no competing interests.

573

574 **Data availability**

575 The data used for the present study are included as supplementary materials:

- 576 - The claw geometry is included in *Supplementary material 12* in Parasolid CAD format.
- 577 - The motion profile is presented in *Supplementary material 3*.

578 The aforementioned data are adequate to define a simulation or design an experiment. In case
579 additional information are required, the interested reader is addressed to the corresponding author (see
580 below).

581

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