Untethered, high-speed soft jumpers enabled by combustion for motions through multiphase environments

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Received 9 March 2020, revised 12 October 2020
Accepted for publication 16 November 2020
Published 10 December 2020

Abstract

Soft robots have been widely studied to accomplish multifunctional on-land tasks in recent years. Here, we develop a type of combustion-enabled soft jumpers that are able to move through multiphase media (e.g. water–air multiphase) with a high-speed of \( \sim 6 \) times body length per second on average and up to \( \sim 9 \) times body length per second at most while the driving time is less than 0.5 s. The reported soft jumpers are driven by extremely expandable silicon-rubber membranes resulted in the combustion of oxygen-propane mixed gas. Experiments are conducted to investigate the multiphase jumping response of the soft jumpers with respect to the premixed gas ratio \( r \) of the combustion. Both numerical and analytical models are developed to investigate the jumping response in terms of the gas amount \( A \), the premixed gas ratio \( r \) and the water depth \( D_w \), and satisfactory agreements are obtained from the comparisons among the experimental, numerical and analytical results.

Supplementary material for this article is available online

Keywords: soft jumpers, high-speed, multiphase environments, combustion

(Some figures may appear in colour only in the online journal)

1. Introduction

Soft robots have been reported with satisfactory performance on environment adaptability and programmable flexible body stiffness, which are expected to address the challenges of traditional rigid robots on unchangeable body shapes, especially for the applications under extreme conditions \([1]\). The majority of studies on soft robotics focus on establishing relations between structural/material design and robot motions to obtain controllable soft robots, which, however, results in the lack of research attention on interactions with multiphase environments such as high-speed motions through multiphase media. The soft robots in the literature, especially the underwater robots, typically face the difficulties in generating high actuation force in a controllable way. Using of premixed gas (e.g. \( \text{CH}_4–\text{O}_2 \)), Shepherd et al developed the combustion-enabled driving actuators, one of the most effective techniques, for on-land high-speed soft robots \([2–5]\), such as the tripod soft jumpers \([3]\) and the soft combustion-driven pump for soft robots \([6]\). More recently, a cephalopod-inspired hydro-jet engine was designed...
to enable soft robots for underwater motions [7]. In general, the literature has mainly focused on developing robotic systems using the combustion method to mimic the movements of natural species or to solve engineering problems [8–17]; on the contrary, few studies have been conducted on investigating the dynamic process of combustion, which leads to the lack of the quantitative relations between gas source consumption and performance of combustion-enabled soft robots.

To control the kinematic performance of combustion-enabled soft robots, two challenges need to be addressed, i.e. investigation of (a) high-speed motions in (b) multiphase environments. The first difficulty of the soft robots is high-speed motions, which is due to the transient physical phenomenon happening with high energy releasing and is hard to control. The second difficulty of the soft robots (i.e. motion through multiple media), due to the complex physical processes, can be particularly defined as how to obtain biomimetic for motions through multiphase environments [18–20].

In fact, studies in the field of bionics have been reported to obtain the motion through different environmental media such as the plankton in mechanical bionics [21]. To the best of our knowledge, however, the developed multimedia robots are only obtained with slow motion. In other words, the recent progress of robots is found as (a) either moving relatively slow but in the multiple environments, or (b) moving fast but in the same environmental medium. Comparing with the existing studies, the combustion-enabled soft robots are observed with the fast motions through multiphase environments. As a consequence, soft robots have yet to be applied to multiphase environments for multifunctional applications in reality.

To fill the research gaps in those two challenges, here, we report the novel type of untethered underwater soft jumpers driven by combustion, which are able to leap out of water and reach an average of 2.5 times body lengths from the water–air interface and 4.5 times of the body lengths from the initial location in a time less than 0.4 s. The reported soft jumpers are driven by reusable, silicon-rubber membranes extremely expanded by the combustion generated by igniting oxygen–propane mixed gas. With accurately maneuvering the jumping motions, the untethered underwater soft jumpers can be potentially used in different environments for different purposes. As a consequence, the soft jumpers are able to mimic the underwater animals with large characteristic length scales (1–100 cm) for jumping out of water [21–25].

The rest of the paper is organized as: section 2 presents the design principle and fabrication processes of the soft jumpers. Section 3 presents the out-of-water testing to investigate the kinematic characteristics of the soft jumpers. Section 4 develops the analytical and numerical models to fully describe the physical process taken place during the actuation, and the results are validated with a satisfied agreement. Section 5 concludes the main findings in this study.

2. Design and fabrication

2.1. Design principle

In this section, we introduce the design principle of the combustion-enabled, high-speed soft jumpers. Figure 1(a) illustrates the detailed structures of the soft jumpers, including the control unit, the weight unit, and the reaction unit. The control unit is designed with a transparent head that contains various circuit components (e.g. single chip micro-computer, and spark generator, etc.). The weight unit is designed with a weight box, which is a threaded round box containing additional mass to balance the buoyancy. The extreme energy releasing phenomenon is designed to take place in the reaction unit, including the energy source, the chamber, the soft membrane, and the holder. The chamber and holder provide a place for the combustion, which allow the hyper-elastic soft membrane to generate large, rapid and recoverable expansion. Figure 1(b) detailed the control and weight units, which consists of gas source and electric source. In particular, the gas source is consisted of the oxygen cylinder, the propane cylinder, and the gas tube to provide flux, fuel, and deliver the reactant gas premixed in certain ratios, respectively. The electric source is consisted of power supply to provide an approximately 9 V DC voltage, and a spark generator to trigger the voltage releasing process when the voltage difference reaches ~200 V [26, 27]. The deformation and actuation principles of the soft jumpers are illustrated in figure 2. After fully injecting the premixed gas into the reaction unit, the spark generator in the soft jumpers is used to ignite the restored reactant. Thereafter, the soft membrane is rapidly expanded in the volcano shape (i.e. concave middle and convex periphery) from 0 ms to 1 ms. It can be regarded as the acceleration process that empowers the soft jumpers. Several circulations of the expansion process later, the soft membrane reaches the highest deformation (i.e. the largest deformation height) by the end of the acceleration period. With the effective control method, using combustion to drive underwater soft jumpers can realize various types of applications.

2.2. Fabrication and experimental setup

The soft jumpers were fabricated using the 3D additive manufacturing technique (e.g. Head, chamber and holder) and molding method (e.g. Membranes). The ultra-expandable membrane was manufactured using silicon-rubber. To compare the kinematic response of the soft jumpers with the previous studies [28–30], we particularly chose Dragon Skin 30 silicon rubber as the raw material for the soft membrane (Smooth-on Inc) [31]. The fabrication process of the soft membrane is shown in figure 3(a). There were five steps in the manufacturing process, including mixing, centrifuging, reversing, defoaming and curing. In the first step, we mixed the gel A and B together with the same volume (70 ml). To deeply mix the gel mixture, in the second step, we used centrifuge with a speed of 1000 rmp...
to mix the gel for 2 min. In the third step, we poured the gel into the 3D printed mould to fit the shape of the soft membrane. Geometric and material properties of the membrane are shown in table 1. Due to the gas bubbles generated during the mixing process, however, the membranes were inhomogeneous without defoaming. Therefore, in the fourth step, we provided the negative pressure environment by the vacuum generator for 15 min to defoam the bubbles. In the last step, we put the mold under constant temperature (i.e. 25°C) for more than 8 h.

Figure 3(b) shows components of the soft jumpers manufactured by 3D printing and computer numerical control machine processing which is a traditional manufacture method. The head, weight box, and the chamber were connected in order, which were fabricated by the transparent material of Acrylic, designed with a hollow to set weight balancing the buoyancy force, and designed with two holes to assemble the gas tube and spark generator.

| Geometric                  | Mechanical        |
|---------------------------|-------------------|
| Diameter (mm)             | Young’s modulus (MPa) | 0.3 |
| Viscosity (cps)           | 30000             |
| Production time (min)     | 45                |
| Thickness (mm)            | Poisson’s ratio   | 0.48 |
| Forming time (h)          | 16                |
| Effective diameter (mm)   | Color             | Translucent |

The gas supply setup is shown in figure 4(a). The oxygen was chosen as the combustion-supporter and the fuel was propane. Check valves and flame reducer were connected to the gas tubes. The oxygen and propane were fully mixed in certain ratios, which was controlled by the electronic flow meter. The premixed gas was input into the chamber of the reaction unit. The chamber unit is completely sealed after the premixed gas is injected. In fact the well-developed out-body-source injection technology is used in this study [3, 5, 7, 31]. The experimental setup for the underwater tests platform is shown in figure 4(b). Due to the transient rapid motion driven by combustion, the optical high-speed camera, at a capture speed of 12000 fps, was set in front of the experimental testing tank. The light boards were installed at both sides of the tank to create clear shooting environment.

3. Out-of-water jumping testing

In this section, we tested the out-of-water jumping performance of the soft jumpers. To obtain the relations between the jumping height, the gas amount, and the premixed gas ratio, a series of underwater jumping-out tests were conducted, and the density plots for the relation are shown in figure 5(a). The premixed ratios ranged from 3 to 6, the premixed gas amounts ranged from 20 ml to 35 ml, and the water depth ranged from
0.25 m to 0.4 m. It is noteworthy that the jumping height is the maximum displacement from the origin location. Generally, the soft jumpers can jump for 0.8 m on average and 1.2 m at most, and when the soft jumpers are set with certain ratio and water depth, the jumping height is increased with the increase of the gas amount. The jumping height is decreased, on the other hand, with the increasing of the water depths. This means that the water environment dominates the water–air multiphase motions of the soft jumpers.

Note that when the gas source is mixed with a ratio between 3 and 6, and the gas amount ranges from 20 ml to 25 ml, the combustion rates were approximately 0% in the experiments, and therefore, we regard it as the insufficient region. When the gas amount is ~35 ml and the premixed gas is 6, the jumpers can generate maximum jumping height, however, due to the over combustion, the soft membrane can only support ~10 times explosions (i.e. unrepeatable). We thus obtained the reasonable ranges for the gas source, which can be used to accurately control the kinematic performances of the soft jumpers. Figure 5(b) shows the leaping-out motion through the multiphase interface (see supplemental video (available online at https://stacks.iop.org/SMS/30/015035/mmedia)). According to the application environments and combustion-induced thrust force of the soft jumpers, the multiphase motions during the entire movement process can be divided into four stages, including the driving, swimming, jumping-out, and falling processes and the driving time is less than 0.5 s. During the driving process, the soft jumpers start moving with a transient rapid acceleration due to the combustion. After approximately 9 ms, the soft jumpers stop accelerating and begin...
swimming underwater. The jumping process starts when the jumpers touch the water–air interface. As the jumpers continue moving in this process, the water surrounding the jumpers is turbulent, and thus, the water surface starts rupturing. The break of the water–air interface is generated by the high-speed conflict of the jumpers. In the end, the falling process follows with the separation between the jumper tails and the water–air interface. Note that the experiments are all conducted under the constrained conditions for guiding the jumpers to leap out of water straightly, and the independence validations are operated which can be shown as figure 5(b). The validation results show that the difference of the maximum jump height between the constrained and unconstrained conditions is less than 5%, which indicates that the influence of the guide axis is negligible.

4. Model validation

4.1. Analytical modeling

An analytical model is developed to fully describe the vertical leaping out process of the soft jumpers. We simplify the shape of the jumpers to be a regular geometry, i.e. hemi-spherically shell head with the height of 20 cm, diameter of 15 cm and...
Figure 6. The analytical modelling principle of the soft underwater jumpers: the propelling process, the approaching process, the interface rupturing process and the falling deceleration process in air.

shell thickness of 7.5 cm, as well as a cylindrically shell body with the length of 12.5 cm and the same diameter and thickness as the head. Figure 6 illustrates the analytical modeling principle of the soft jumpers, which consists of the propelling, approaching, interface rupturing and falling processes. In general, the jumpers are able to reach high acceleration by the combustion in the propelling process. At the initial moment, the pressure generated by the combustion due to the reaction can be written as [31]

\[ p = A_c \left( 1 - \frac{\gamma w_c V_1}{R_1 V_0^2} \right) e^{-\frac{e_0 + \gamma V_1}{\gamma T}} + B_c \left( 1 - \frac{\gamma w_c V_1}{R_2 V_0^2} \right) e^{-\frac{e_0 + \gamma V_1}{\gamma T}} + \frac{\gamma^2 w_c e_0 V_1^2}{V_0^2 \delta^2}, \]  

(1)

where \( A_c \) and \( R_1 \) are the high-pressure coefficients, \( B_c \) and \( R_2 \) are the medium pressure coefficients, and \( w_c \) is the overall pressure coefficient. \( e \) is the specific internal energy given as \( e = \frac{\gamma}{\gamma+1} \), where \( e_0 \) is the initial specific internal energy of the TNT. \( V_c \) is the specific volume that can be calculated as \( V_c = \frac{V_0}{V_1} \), where \( V_0 \) and \( V_1 \) are the expanded gas specific volumes generated by the combustion and the initial specific volume of the TNT, respectively. \( \delta \) is balance coefficient. Using the TNT method to transform the explosion into the equivalent mass TNT method, it can be written as

\[ W_{\text{TNT}} = \frac{1.8aWQ}{Q_{\text{TNT}}}, \]  

(2)

where \( W_{\text{TNT}} \), \( a \), \( W \), \( Q \) and \( Q_{\text{TNT}} \) are the weight of TNT, TNT equivalent weight of combustible gas, weight of the reactant, combustion heat of the reactant and combustion heat of TNT, respectively. Considering the large deformation of the membrane, the governing equation of the largely deformed membrane might be written as [31],

\[ \frac{d^2}{ds^2} (\alpha S_1) + \frac{p^2}{32S_1^3} = 0, \]  

(3)

where \( \alpha = \frac{E}{h}, S_1 = \frac{\delta e_0}{\gamma T} \) and \( P = \frac{\phi d p}{d t} \). Note that \( P \) is obtained as

\[ P = A_c \left( 1 - Ar \cdot \frac{\varphi w_c}{R_1 V_0^2} \right) e^{-Ar \cdot \frac{e_0}{\gamma T}} + B_c \left( 1 - Ar \cdot \frac{\varphi w_c}{R_2 V_0^2} \right) e^{-Ar \cdot \frac{e_0}{\gamma T}} + A^2 r^2 \cdot \frac{\varphi^2 w_c e_0 V_1^2}{V_0^2 \delta^2}, \]  

(4)

Detailed derivations can be found in [31].

The equivalent concentrated force \( F \) might be written in terms of the combustion pressure \( p \) as

\[ F = \frac{R^2 h^2}{4h^2 E} p, \]  

(5)

where \( h \) and \( E \) are the membrane thickness and Young’s modulus of silicon rubber, respectively. When the combustion stops, the approaching process starts, and the jumpers keeps swimming upward to the interface. The interface rupturing process starts when the head of the soft jumpers touches the water surface, which can be particularly divided into two periods: the preliminary stage and the ending stage, in which the jumpers head interacts with the multiphase interface and the body of the jumpers goes out of water surface. After shedding of the boundary layer, in the falling process, the jumpers are only affected by the self-weight.

The driving force of the soft jumpers can be written as

\[ F_t = F_1 - F_d - F_a, t \in [0, \lambda], \]  

(6)

where \( F_1, F_d, F_t \) and \( F_a \) are the calibrated thrust force in section 4.2, the drag force of water, the resultant force of the soft jumpers, and the added mass force, respectively. The drag force \( F_d \) is written as

\[ F_d = \frac{1}{2}\rho_{\text{water}}C_dSV^2, \]  

(7)

where \( \rho_{\text{water}}, C_d, S \) and \( V \) represent the density of water, the drag coefficient, the upstream area, and velocity of the soft jumpers. Based on previous study about drag coefficient [32], \( C_d \) is defined as a function of time as

\[ C_d(t) = \frac{A}{\text{Re}(t)} \times [1 + \varphi(\text{Re}(t))], \]  

(8)

where \( A = 24 \) and \( \text{Re} \) are the viscous drag coefficient and the Reynolds number, respectively [30]. \( \varphi \), the shape drag coefficient, is written as

\[ \varphi = 1.375e^3 - 1.3e^2 + 0.36e + 0.104, \]  

(9)
where $e$ is the eccentricity of the soft jumpers. It can be seen from figure 6 that $e = 0$ when no steering occurs to the jumpers. The Reynolds number is the function of time which can be shown as

$$\text{Re}(t) = \frac{\rho_{\text{Water}} L \cdot V(t)}{\mu},$$

(10)

where $L$ and $\mu$ are the characteristic length and the dynamic viscosity of water that equals to $1.01 \times 10^3$ Pa·N, respectively. Due to the relatively high speed of the soft jumpers, gravity dominates the out-of-water jumping. The increment of the gravity can be obtained as

$$\Delta G = mg - \rho_{\text{Water}} g h_{in} V_{in},$$

(17)

where $h_{in}, V_{in}$ are the underwater height and the volume of the jumpers, respectively.

The ending stage of the interface rupturing process can be calculated using equation (18) as well. However, $X$ is changed with the different outline of the jumpers as

$$X = 0.0122 \pi \rho_{\text{jumpers}} D^2 V^2,$$

(16)

Finally, the falling process of the jumpers can be written as

$$F_i = G,$$

(19)

where $G$ is the gravitational acceleration.

### 4.2. Measurement of the thrust force

In order to obtain the thrust force $F_i$ in equation (14), we conducted the experimental calibrations on the combustion-expanded soft membranes in the soft jumpers. The experimental setup is shown in figure 7(a). To obtain the relations between the thrust force generated by combustion and time, the combustion-driven calibration platform was designed with the base, soft silicon-rubber membrane, pushing plate, axles, weights, and limitation. The base was designed with a sealed combustion chamber which contains an inlet hole and an outlet hole. The combustion was triggered by the spark ignition, and the generated high pressure expands the soft silicon-rubber membrane to push the plate. The displacements of the plate were captured by the optical high-speed camera with a speed of 12,000 fps.

Figure 7(a) illustrates the thrust force measurement process resulted in the combustion-induced large deformation of the membrane. During the time period of 0–8.7 ms, the membrane overcame the weights and provided the extremely rapid thrust force. The thrust force equaled to the gravity at the explosion limit ($t = 8.7 \text{ ms}$). During the time period of 8.7–20 ms, the plate continued moving upward due to the inertia force, and the plate stopped attaching at the membrane the contact limit ($t = 20 \text{ ms}$). Thereafter, the rest of the motions are regarded as the upcasting motion. The driving time of the combustion
Figure 7. The combustion load experiments for force measurement: (a) experimental setup, actuation process, and displacement results of the pushable plate and (b) force results.

Table 2. Calibrated forces in different gas amount and ratios (Unit: kN).

| Gas amount (ml) | Premixed ratio | 20   | 25   | 30   | 35   |
|----------------|----------------|------|------|------|------|
| 3              | 4.20           | 4.60 | 4.80 | 4.90 |
| 4              | 4.00           | 4.65 | 4.70 | 4.75 |
| 5              | 3.00           | 3.60 | 4.10 | 4.50 |
| 6              | —              | 3.80 | 4.10 | 4.20 |

(i.e. the maximum deformation of the membrane) is less than 0.1 s, and the characteristic speed (i.e. the maximum velocity of the membrane in combustion process) is between 40 m s\(^{-1}\) and 90 m s\(^{-1}\). In addition, the reacting time of the combustion (i.e. time delay between the ignition and combustion) is less than 1% of the driving time. We fit the force data into an empirical formula to describe the thrust force with the time, which can be written as

\[ F_T = \psi \cos (\chi t) \]  \hspace{1cm} (20)

where \( F_T \), \( \psi \), \( \chi \), and \( t \) are the thrust force, combustion magnitude, the time period which is 180 rad s\(^{-1}\), and time, respectively. The experiment cases composed of four gas amount (i.e. 20 ml, 25 ml, 30 ml, 35 ml) and four gas ratios (i.e. 3, 4, 5, 6) and calibrated results are presented in figure 7(b) and table 2. The detailed parameters in the theoretical model are provided in Table 4. The density plots show the relations between the thrust force and the time under different mixing ratios of the premixed air. The maximum values of the thrust force appear at the beginning of the propelling processes, and forces in all cases become 0 N at the time of 8.7 ms, which is consistent with the reported explosion limit. The overall combustion magnitudes \( \psi \) are decreased with the increasing of the premixed ratio, which are the same as the reported interface rupturing performance of the soft jumpers.

4.3. Numerical modeling

The jumping process of the soft jumpers is numerically simulated in FLUENT, ANSYS [34], as shown in figure 8(a). Since the combustion-enabled soft jumpers leap out of the water with relatively high impact velocity, the fluid field is critically disturbed, and thus, the transient force (i.e. the thrust force generated by the combustion) need to be applied at the bottom of the soft jumpers, which makes the jumpers move in the water–air multiphase fields. The counterforces (i.e. the summation of the drag force, added mass force and gravity) prevent the jumpers from jumping out of water. The dynamic mesh method is applied in the numerical simulations, which allows the elements to deform using the spring performance assumption. When the deformation of the elements reaches the threshold, the global mesh is automatically re-meshed to ensure the accuracy of the calculation. For the hydrodynamic simulation, a 3D numerical model is developed, and the governing equations are the time-averaged incompressible continuity equation and Navier–Stokes (N–S) equation. The volume of phases model is used to solve the multiphase fluid dynamics phenomenon. The standard \( k-\varepsilon \) viscous model is used to ensure the calculation stability. The semi-implicit method for the pressure-linked equation algorithm is used to solve the coupling problem between the pressure and velocity. Table 3 shows the detailed information in the numerical simulations.

4.4. Comparisons and validation

The kinematic performance of the soft jumpers are experimentally, numerically and theoretically obtained, and next, the comparisons of the jumping response are presented in figure 8(b). The density plots show the relations between the thrust force generated by the combustion, the time and the displacement, which are ranged as \( F_T \in [3, 5] \) kN, \( t \in [0, 0.4] \) s, and \( \text{Height} \in [0, 0.8] \) m, respectively. It can be seen that the soft jumpers jump upward rapidly from the time period of 0–0.1 s, which are caused by the thrust force generated by the combustion. During the time period of 0.1–0.35 s, the soft jumpers are critically decelerated due to the gravity in the air and the decreasing of the kinetic energy. After 0.35 s, the jumpers start falling back to the water. Due to the simplifications applied the fluid dynamic parameters (i.e. the drag
Table 3. Detailed information in the numerical simulations.

| Mesh                  |                  |                  |
|-----------------------|------------------|------------------|
| Nodes                 | 3529             |                  |
| Elements              | 17912            |                  |
| Minimum size (mm)     | 0.795            |                  |
| Maximum face size (mm)| 79.477           |                  |
| Maximum tet size (mm) | 158.950          |                  |
| Model                 | Volume of fluid  |                  |

| Multiphase model      |                  |                  |
| Number of Eulerian phases | 2                |                  |
| Volume fraction parameters | Implicit        |                  |
| Volume fraction cutoff | $1 \times 10^{-6}$ |                  |

| Viscous model [34]    |                  |                  |
| $C_\mu$               | 0.090            |                  |
| $C_{1\varepsilon}$    | 1.440            |                  |
| $C_{2\varepsilon}$    | 1.920            |                  |
| $\sigma_k$            | 1                |                  |
| $\sigma_\varepsilon$  | 1.300            |                  |
| Scheme                | PISO             |                  |

| Solution methods      |                  |                  |
| Neighbor correction   | 1                |                  |
| Skewness correction   | 1                |                  |

Table 4. Detailed information in the analytical predictions.

| Parameters for jumpers | $m$ (kg) | 3.09 |
|------------------------|---------|------|
| $D$ (mm)               | 150     |      |
| $\rho_{\text{jumpers}}$ (kgm$^{-3}$) | 1000    |      |
| $\rho_{\text{water}}$ (kgm$^{-3}$) | 1000    |      |

| Parameters for fluid   | $C_d$ | 2.3  |
|------------------------|-------|------|
| $\alpha$               | 0.7   |      |
| $D_W$ (mm)             | 300/350/400 |     |

The jumping height of the soft jumpers is then compared with the experimental, numerical and analytical results, are shown in figure 9. The maximum displacement from the multiphase environments results are particularly compared under different premixed air ratios and water depths. In general, the reported soft jumpers are able to jump out of water for averagely 0.5 m with the maximum of 0.6 m. The relations between the maximum jumping height and gas amount indicate the quadratically increasing pattern. The increasing of the displacement between the adjacent points are shown in figure 9, which shows that the gas amount selected in this study are adequate to provide accurate displacement control for the soft jumpers. In the same conditions of the premixed ratio, the overall displacements decrease with the increasing of the water depth. Under the same conditions of the water depth, the increasing rate of the overall displacement is decreased with the increasing of the premixed ratios. The unstable combustion generated in extreme conditions, the guide axles and the interface assumption are the main reasons of some disagreements in figure 9. Combustions of the small premixed gas amount are typically unstable. For example, when the gas amount is 25 ml (i.e. row 4 column 1 in figure 9), the reactant amount reaches the minimum boundary of the combustion amount. Although these factors slightly affect the accuracy of the experimental results, the overall differences of the comparisons in this study are less than 15%, which are acceptable, especially for the reported transient motions under the extremely powerful combustion force. Generally, the reported soft jumpers are able to jump and reach the maximum height point within 0.4 s on average with the longest of 0.5 s. A linearly increasing pattern is obtained for the relations between the time consumptions for reaching the highest location and gas amount. The time consumption is reduced with the increasing of the water depths, and the increment rates are reduced with the increasing of the premixed ratios. Good agreements are obtained with the differences of less than 15% in all cases.
5. Future trends of the soft jumpers

The reported multiphase soft jumpers can be applied in different scenarios. However, it is worthwhile to point out that an efficient and easy-to-carry gas source is required to provide sufficient raw materials for continuous jumping motions, such that the combustion-driven soft jumpers can be implemented for long-distance applications. As the power supply, additionally, the expandable soft membranes need to be optimized to obtain higher stiffness and better recoverability after the extremely large deformations under combustion. Moreover, multiple reaction units can be designed to the soft jumpers such that the thrust force $F_T$ does not coincide the neutral axis, which leads to the controllability over the moving directions of the jumpers.

6. Conclusions

This study developed the combustion-driven untethered underwater soft jumpers which is able to jump through the water–air multiphase environments with the average of 0.8 m and the maximum of 1.2 m in height. We first measured the thrust force enabled by combustion and found that the driving time is less than 0.1 s, the characteristic speed is between 40 m s$^{-1}$ and 90 m s$^{-1}$, and the reacting time of the combustion is less than 1% of the driving time. Next, the experiments were conducted to obtain the relations between the jump height $H$, the gas amount $A$, the premixed gas ratio $r$, and the water depth $D_W$. Analytical and numerical models were developed to compare with the experimental results and satisfactory agreements were obtained with the differences of less than 10%. Empirical formulas were obtained to predict the kinematic performance of the soft jumpers. In this study, we obtained the interaction performances between the jumpers and the air-water interface. The interface-rupturing period, due to the decreasing of the buoyancy, is simultaneously a rapid deceleration process for the jumpers, which is consistent with the previous studies [21]. From the mechanical response perspective, the reported untethered underwater soft jumpers can generate high speed motions enabling it to leap out of the multiphase environments. The entire motion processes, which include the interface-rupturing process, are experimentally, numerically and theoretically analyzed in this study. The transient driving method (TDM) enabled by combustion is a potential way to realize high-speed motions of soft jumpers, especially underwater, however, more creative designs are needed to get rid of the bulky fuel cylinders and valves.
Acknowledgments

This study is partially supported by the National Key Research and Development Program of China (Grant No. 2017YFC0305905), National Natural Science Foundation of China (Grant No. 11672267), and Fundamental Research Funds for the Central Universities (Grant Nos. 2017XZZX001-02A and 2020-KYY-529112-0002). PJ acknowledges the Startup Fund of the Hundred Talent Program at the Zhejiang University.

Appendix A. Experimental results

Figure S1 is the density plot of experimental relation between gas amounts, water depths and maximum jump heights in different premixed ratios. Figure S1 shows the same results as figure 5(a) in a different view. Table S1 shows the statistical analysis results of the experiments.

Appendix B. Comparison

Figure S2 is the comparison result between theoretical and numerical results, which presents the same message as the figure 8(b) for a further supplement. Figure S3 is the reaching-top time comparison between the theoretical and the numerical results.

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