Passive pre-tensioning of buoyancy engines for fail-safe and energy efficient depth control

Harry Redfern[1], Guy Denton[1], Miquel Massot-Campos[1], Blair Thornton[1,2]
[1] *Faculty of Engineering and Physical Sciences, University of Southampton, Southampton, United Kingdom*
[2]*Institute of Industrial Science, The University of Tokyo, Tokyo, Japan*

***Abstract*—This paper describes the development and testing of a novel pre-tensioned variable buoyancy engine (VBE) that has two major advantages over traditional VBEs, i) fail safe behaviour, where the device expands to achieve maximum buoyancy in the event of power loss, and ii) reduced energy consumption when varying buoyancy at high hydrostatic pressure. The system achieves these properties by using a set of springs to push out a piston that varies the device's displacement. This paper develops the theory to size these springs for fail-safe and energy efficient operation at different depths. Practical experiments are carried out under simulated hydrostatic pressures using a prototype pre-tensioned VBE designed according to the developed theory. We compare two methods of sealing the piston. Both methods demonstrated fail-safe response when power is lost, and achieved a maximum energy reduction of 25 % compared to VBEs with no pre-tension under our experimental conditions. We discuss the implications of our results for different types of autonomous submersible mission profiles and make suggestions for future work.**

I. Introduction

Thousands of autonomous submersibles currently operate to monitor the state of our ocean [1]. Although the types of vehicles and their applications vary, all have the ability to move up and down the water column. A common method to achieve this is to use a variable buoyancy engine (VBE). VBEs work by displacing a variable volume of water through expansion or contraction of a piston or bladder. Since the displaced volume changes for a constant mass, this action achieves a net change in buoyancy that can be used for vehicle control. They allow for efficient vertical travel and are used on underwater gliders and floats that perform multiple depth profiles of the water column (see figure 1). VBEs are also used on seafloor monitoring platforms such as autonomous underwater vehicles (AUVs), especially in applications where the energy consumption of the vehicles needs to be minimised. Achieving near neutral buoyancy means that the AUVs can maintain their depth or a fixed target altitude off the seafloor without using other actuators to continuously compensate for non-zero buoyancy. Recently, several groups have been looking at Lagrangian imaging floats [2], [3]. These platforms dive and maintain a fixed altitude off the seafloor, taking images of the seafloor for long periods (up to several days) while passively drifting on underwater currents (see figure 1). Minimising the energy used to maintain a fixed altitude is critical for achieving long endurance.

From the above perspectives, traditional VBEs have two undesirable properties. First, electrical energy is needed to actively expand their volume and so increase buoyancy. In the event of a loss of power (e.g., through some failure or depletion of their supply), VBEs cannot expand and so vehicles that rely on them for depth control cannot reliably return to the surface for recovery without some additional safety feature (e.g., use of emergency drop weights [4]). As a result, many hundreds of Argo floats sink to the seafloor by design at the end of their battery life, which raises concerns regarding the sustainability of current use practices. Next, the amount of energy needed to achieve buoyancy control increases with depth due to the larger hydrostatic pressures that need to be overcome. At least half of VBE control is done at depth (e.g., gliders and floats), with VBE equipped seafloor observation platforms (e.g., AUVs and Lagrangian imaging floats) performing the majority of VBE control at depth to maintain neutral buoyancy or control depth during seafloor observation. These limitations motivate research into novel VBE design concepts, such as the pre-tensioned VBE, first described in [5]. In this paper, we further develop the concept of a pre-tensioned VBE and present the first experimental demonstration that addresses the disadvantages of traditional VBEs.

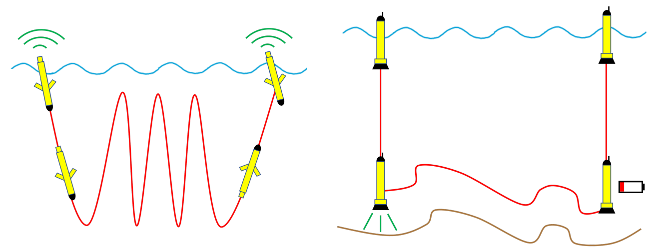

Fig. 1. Illustration of contrasting submersible dive profiles, showing typical glider (left) and typical Lagrangian imaging float (right) missions

II. pre-tensioned VBE design concept

The use of passive pre-tension can potentially overcome undesirable properties of traditional VBEs. In [5] the authors proposed how the potential energy physically stored in a contracted spring could be used to achieve this by working against the pressure head (Fig. 2). The criteria for design are that first, the pre-tensioned VBE should exhibit fail-safe behaviour, whereby the system returns to the surface in the event of power loss so that it can be recovered at some later point. To achieve this however, it is necessary for the springs that provide pre-tension to be sized correctly so that at any depth shallower than the system's design depth, the

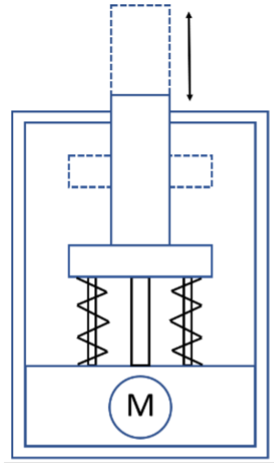

Fig. 2. PVBE diagram.

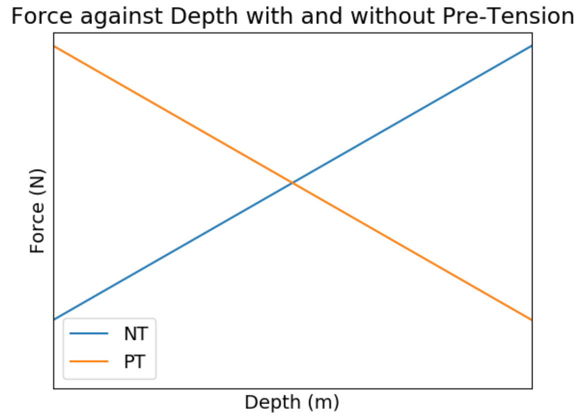

Fig. 3. Reversal of energy depth relationship when PT is applied

equilibrium position of the piston without electrical intervention should be at full displacement. This would achieve the largest possible buoyancy of the VBE and so maximise the chances of the platform surfacing. The second design criteria is that the pre-tensioned VBE should have the potential to increase mission duration due to operational energy savings. Introducing pre-tension (PT) to the system reverses the energy-depth relationship seen in traditional VBEs that have no pre-tension (NT). NT systems require more energy at deeper depths when increasing buoyancy as the motors they use work directly against the hydrostatic pressure forces acting on the piston (Fig. 3). With correctly designed PT systems however, the motors work against the springs to prevent them from extending, and so increased hydrostatic pressure reduces the force that needs exerting by the motor. Increasing the force exerted by the springs increases the force required to move the piston, effectively translating the orange line in the graph upwards. This reduces the range of depths where PT systems operate more energy efficiently (i.e., the intersection point of the orange PT and blue NT curves translates right). Therefore, when sizing the system the PT amount should be enough to return the system to full displacement at the rated depth, but small enough to allow for a large range of depths where energy efficiency is improved.

A. Design Theory

To correctly size the PT springs, it is necessary to consider the forces that act on the system. The free body diagrams in figure 4 illustrate that although the spring forces always oppose the hydrostatic pressure, friction in the seals used to make the piston water tight always acts against piston motion, and so acts in opposite directions during contraction and expansion.

The torque required by the motor to move the piston depends on its direction of travel. Equations 1 and 2 show the torques needed for piston contraction and expansion using a lead screw.

When expanding and contracting torques are averaged for systems with and without seal friction considerations, it can be seen that the average torque requirement is lower when seal friction is not present (NF) (figure 5).

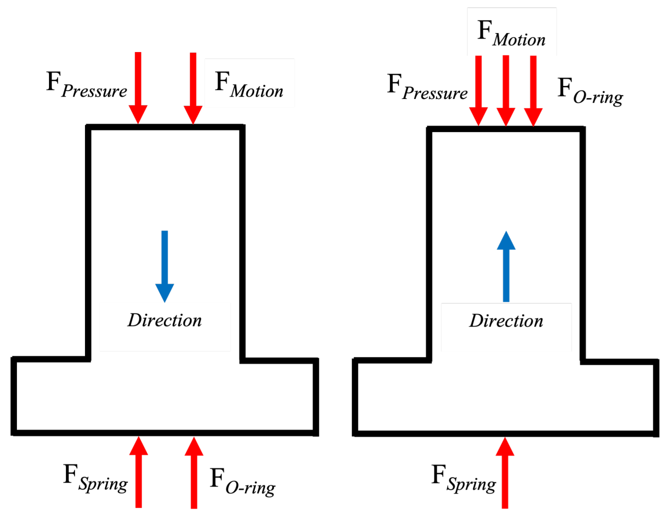

Fig. 4. Free body force diagram for contraction (left) and expansion (right) of the piston

$$\tau_E = \frac{F_{Motion} d_m}{2} \left(\frac{\pi \mu d_m - l}{\pi d_m + \mu l} \right) \tag{1}$$

$$\tau_C = \frac{F_{Motion} d_m}{2} \left(\frac{l + \pi \mu d_m sec(\alpha)}{\pi d_m - \mu l sec(\alpha)} \right) \tag{2}$$

τ is the torque required by the motor in Nm, μ is the coefficient of friction, d_m is the mean diameter of the screw in m, l is the lead distance in m, and α is the lead screw's pitch angle in radians.

B. Prototypes

Figure 6 shows the two setups that were developed and tested in this work. For both setups, an actuated lead screw is used (see table I for properties), which is used to control the piston's position. The piston's displacement is measured using

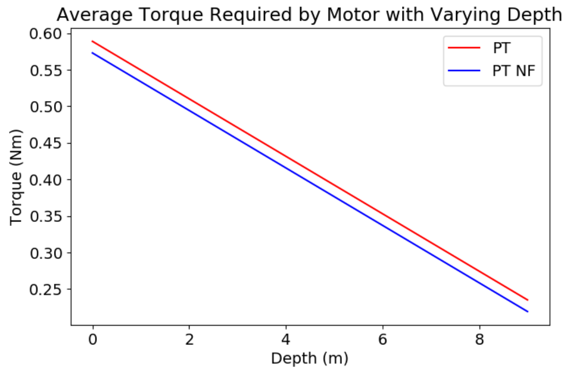

Fig. 5. Average Motor Torque required as depth varies

an infra-red range sensor contained in the base. The piston has a diameter of 50 mm, resulting in a maximum volume displacement change of 196ml, or approximately 2 N change in buoyancy. Springs are used to provide pre-tension, and these can be seen on the guide rails of the piston. The design depth rating for this initial prototype was set to 3.2m for ease of experimentation, where introducing stiffer springs would allow for deeper use. The spring setup in the prototype consists of 4 parallel pairs of 2 springs in series. Each spring has a spring constant 1880 Nm^{-1}, free length 100 mm, diameter 20 mm and minimum working length 35.6 mm. This equates to single spring of spring constant 3760 Nm^{-1} and free length 200mm. When pre-tensioned by 10 % they exert a force of 75 N, with a maximum compression force of 480 N, where this provides a safety factor of 1.2 for the design depth. Removing the springs results in the prototype behaving in the same way as a standard piston actuated VBE. The previous section described the effects of friction on the torque, and so energy, needed for actuation. In order to investigate this point, two methods to seal the piston were developed; first using a standard O-ring piston seal (shown in the left of figure 6), which has high-friction in the system, and second a bellows seal (shown in the right of figure 6), which avoids sealing friction on the piston while retaining water-tightness.

TABLE I
HIGH-HELIX LEAD SCREW THREAD PROPERTIES

Property	Symbol	Value
Coefficient of friction	μ	0.2
Mean screw diameter	d_m	8.5 mm
Lead distance	l	12 mm
Lead screw pitch angle	α	0.376 rad

III. METHOD

Experiments were carried out for both the O-ring and bellows sealed designs, both with (i.e., OP, BP) and without (i.e., ON, BN) spring pre-tensioning. Two types of experiment were designed to investigate whether our success criteria had been met;

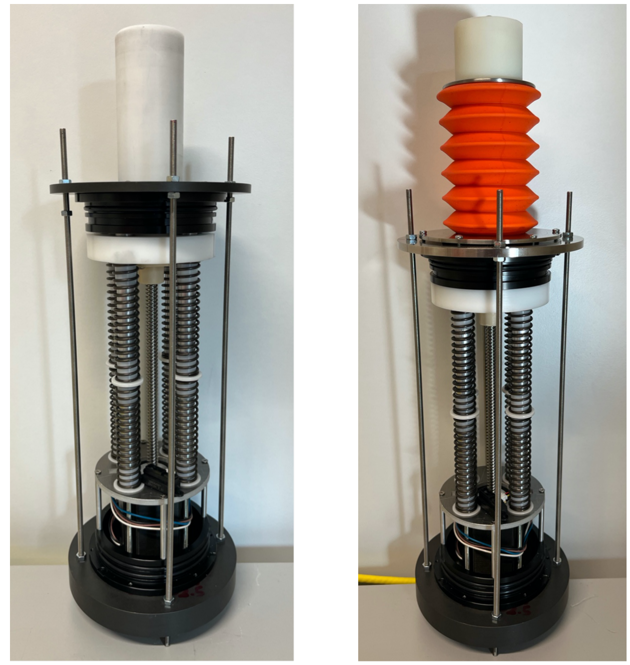

Fig. 6. pre-tensioned VBE prototypes developed and tested in this work. The left image shows the O-ring pre-tension (OP) configuration, and the right image shows the bellows pre-tension (BP) configuration. Both setups are shown with the piston (in white) at full extension, where water-tight housing tube has been removed so that internal components can be seen. The springs located on the guide rails of the piston provide the pre-tension effect. Removal of these results in behaviour identical to a standard piston driven VBE setup, corresponding to O-ring no-pre-tension (ON) and bellows no-pre-tension (BN) configurations.

- Fail-safe behaviour: The piston was contracted to minimum displacement position, and then power to the system was cut off to simulate power failure. Experiments were performed on land, using a weight of 6.3 kg on the vertically oriented piston to simulate the pressure head experienced at the rated depth of 3.2m. Fail-safe behaviour is assessed by monitoring the piston's until it reached a steady state, where passive return to maximum displacement would represent success.
- Energy use: The piston was controlled follow a returning displacement profile, or RP profile, that covered the full stroke of the setup in surface and design depth equivalent conditions. Current and voltage were measured to determine power consumption and so determine energy efficiency. The data allows the suitability of pre-tensioned VBEs for different types of submersible operation (e.g., gliders, floats, AUVs).

A. Control and Data Acquisition

The circuitry was Arduino based, and used a NEMA23 stepper motor controlled by an STR8 driver (Applied motion). The following data was taken simultaneously at a sampling rate of 1 Hz for all experiments:

1) Piston displacement
2) Current drawn by the stepper motor driver
3) Voltage supplied at the stepper motor driver

The displacement was measured using an infrared range sensor capable of measuring distances between 4 and 30cm that was built into the base unit. A low pass filter was used to remove any high frequency noise from the signals, where a cut-off frequency of 6.8 kHz was used to remove noise from the stepper motor, which has winding signal frequencies of 10kHz and above [6].

An ACS712 current sensor was used with an accuracy of ±1.5 %, and a sensitivity of 185 mV/A. When combined with the 10-bit analogue to digital converter (ADC) that is standard in the Arduino, a theoretical measurement resolution of 9.8 mA is achieved, which is suitable considering the operational current range of the stepper motor that was recorded. Voltage was recorded using a potentiometer to determine power use of different setups. The power supplied to the Arduino and above sensors was separate from the stepper motor driver power supply so that measurements could continue when power to the stepper motor was cut during fail-safe behaviour experiments.

IV. Results

A. Fail-safe behaviour

The fail-safe mechanism was tested three times for each setup under conditions equivalent to the system's design depth. The piston was powered and drawn to minimum displacement before power to the stepper motor was cut. Figures 7 to 10 show the results for the four different setups. In the figures, the green background shows when a fail-safe test is taking place, whilst the yellow background shows when the system is being drawn in or out to reset the test.

1) O-Ring Design Results: Figure 7 shows results for the ON setup, where fail-safe behaviour does not occur when the system is used without pre-tension springs - as expected. The figure shows a small step in displacement that occurs each time the power is lost of around 1cm. This is a result of the prototype 'relaxing' when the motor stops exerting torque. The coupling between the lead screw and the piston and motor has a few mm of play upwards and downwards, where this combined with the relaxation of the O-ring rubber cause this motion to occur. This displacement change, however, is too small to constitute fail-safe capability.

When pre-tension is introduced to the system (figure 8), successful fail-safe behaviour is demonstrated. When power is cut to the system and the current drops to 0, the energy stored in the compressed springs passively increases the displacement of the plunger. It can be seen that the piston initially extends out rapidly, but does not reach its maximum expansion and instead settles after recovering just over 70% of the buoyancy available in the system. This levelling off occurs since the force exerted by the spring decreases linearly with extension, and becomes unable to overcome the combined pressure head and friction in the O-ring seal. Although this problem could be overcome by increasing how much the springs are compressed in this extended displacement state. Although maximum buoyancy does not occur in this experiment, in a practical scenario, as long as a net positive buoyancy can be achieved, the pressure

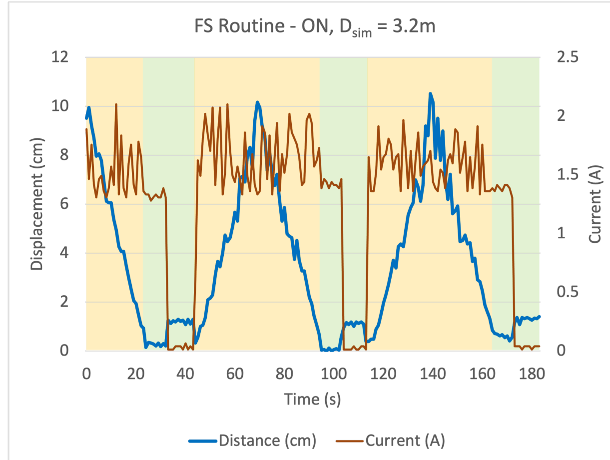

Fig. 7. Fail-safe experiment for the ON setup (O-ring no pre-tension)

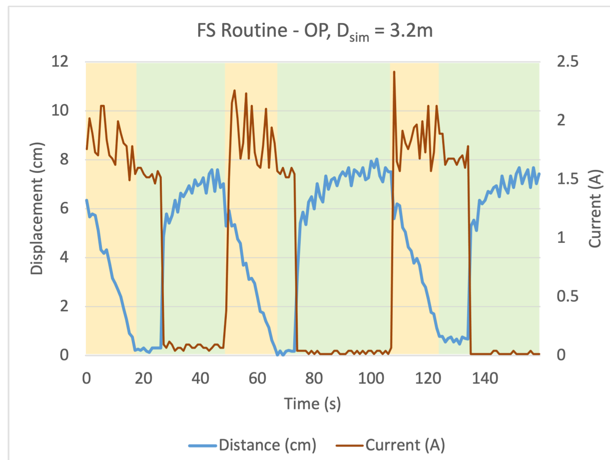

Fig. 8. Fail-safe experiment for the OP setup (O-ring with pre-tension)

head would decrease as the submersible's depth decreases, and it is possible that maximum displacement would be achieved.

2) Bellows Design Results: Figure 9 shows results for the BN setup, where fail-safe behaviour does not occur when the system is used without pre-tension springs as expected. The small step change that is observed is due to 'relaxation' of the system, as described with the ON setup.

When PT is introduced to the system (figure 10, fail-safe behaviour is shown since when power is cut to the system and the current drops to 0, the system passively changes the displacement of the plunger. In this case, the system recovers 90% of the buoyancy. Avoiding friction acting on the piston in the design means the springs can return the system closer to full displacement as they only need to overcome the pressure head working against them. The system does not quite reach maximum displacement due to the internal friction involved in turning the motor. Again, this can be overcome by accounting for this friction in the design, and in a practical scenario, as the system floats to the surface, the pressure head will decrease and is likely to return to d_{Max}.

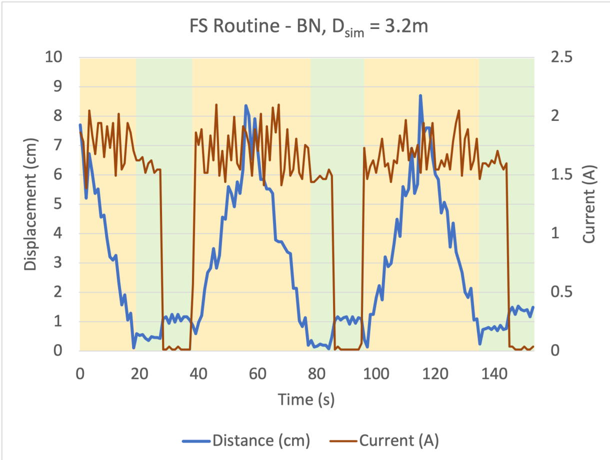

Fig. 9. Fail-safe experiment for the BN setup (bellows no pre-tension)

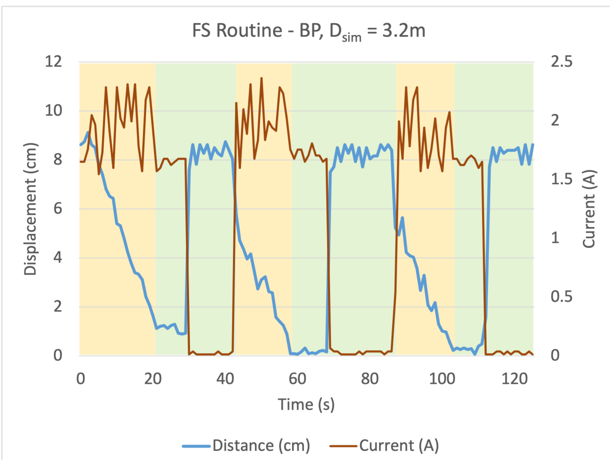

Fig. 10. Fail-safe experiment for the BP setup (bellows with pre-tension)

3) Discussion of fail-safe behaviour: The fail-safe behaviour of the proposed system offers a unique advantage over traditional VBEs, since these are not capable of fail-safe behaviour without an additional safety mechanism (e.g., drop-weights). The results show that the novel use of pre-tensioned springs in the design achieve significant recovery of buoyancy when power to the system is lost. Of the two pre-tensioned designs, the bellows is more reliable at returning to maximum displacement. The consideration that was made for friction in the system, and the subsequent avoidance of this friction improves fail-safe performance, whereas the O-ring system was observed to stick when approaching maximum displacement. In both cases, modelling of frictional effects during spring sizing would make full buoyancy recovery possible, although there would be some cost in terms of using heavier springs. It is worth noting, that as long as a net positive buoyancy can be achieved at the design depth, the shallower depths the reduced pressure head would likely allow for full recovery of buoyancy, although further tests are needed to confirm this. Simulating a variable pressure head is challenging in dry tests, so such tests are recommended to be carried out in water. However, while further improvements to the design are possible, the key novel behaviour of significant buoyancy recovery upon power loss has been successfully demonstrated by both pre-tensioned setups.

B. Power consumption

Figure 11 shows the displacement time plot used for RP tests. The piston was drawn fully in and out repeatedly for 5 minutes, this was repeated for 3 runs for each system configuration. A current average and standard deviation measurement was then calculated. The voltage to the stepper motors remained constant throughout the experiment, and so current and power are directly proportional.

Fig. 11. Displacement time plots of RP tests for BP configuration at the surface

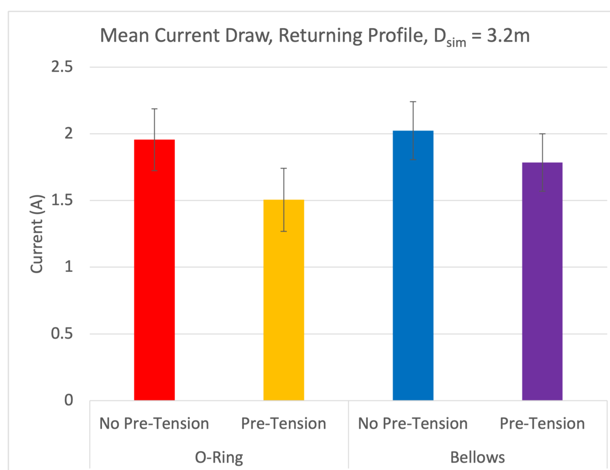

Fig. 12. Mean current draw during RP tests for all configurations, D_{Sim} = 3.2

When operating at the rated depth (figure 12), both the pre-tension VBE designs benefit from the use of springs with a measurable decrease in the average current draw in both cases. This is due to the flipped energy depth relationship (figure 3) caused by the springs counteracting the pressure head. The OP system experiences a reduction of 0.45 A compared to ON, and the BP system a reduction of 0.24 A compared to BN, corresponding to a reduction of power consumption of 23 % and 12 % in the OP and BP setups respectively.

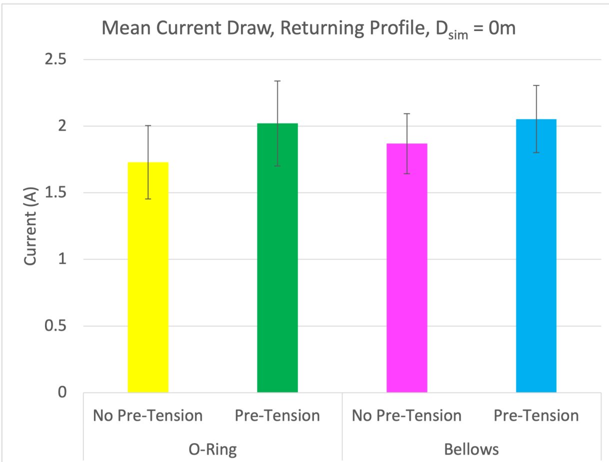

Fig. 13. Mean current draw during RP tests for all configurations, $D_{Sim} = 0$

The opposite relationship is observed when the system is in conditions corresponding to surface operation (figure 13). When the pressure head is removed from the system, the OP system draws an average of 0.29 A more than ON, and the BP system 0.19 A more than B, corresponding to a 17 % and a 10 % increase in the OP and BP setups respectively. This is expected due to the reversal of the energy depth relationship.

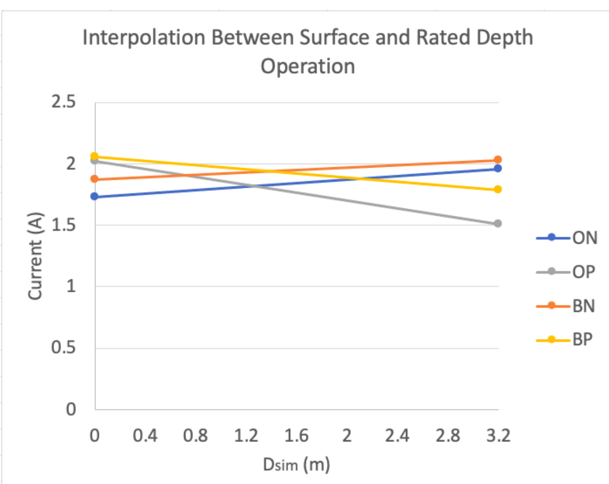

Fig. 14. Interpolation between mean current draw at surface and at depth.

Both pre-tensioned designs operate with less power when operating at depth compared to in shallow water (figure 14) because the holding force required at depth is smaller when the pressure head opposes the pre-tension force. At rated depth, the OP design uses 0.28 A less than BP, and is more energy efficient. This is because the concept behind the BP configuration was to avoid friction on the moving piston. However, regarding energy usage the friction is beneficial as when the motor is required to hold the system, static friction assists the motor in achieving the necessary holding torque, hence reducing the torque required from the motor. Whilst during motion friction is detrimental, the results suggest that energy usage is dependent on holding torque and not the torque during motion. At the surface, however, this effect is not as noticable since the required holding force of the pre-tensioned systems is larger, and the static friction does not vary. Therefore, the seal friction accounts for a smaller proportion of the holding force.

C. *Discussion of power consumption*

The power required by pre-tensioned VBEs to operate decreases as depth increases up to their design rating. Traditional, non pre-tensioned VBEs have the opposite relationship. At shallow depths, VBEs offer the more efficient means of controlling buoyancy. When operating at the rated depth, pre-tensioned VBEs are more efficient because the springs overcome forces due to the pressure head. Of the two pre-tensioned configurations, the use of O-rings was found to be more energy efficient than use of the bellows, since the energy usage depends more on the holding torque, where friction in the O-ring seal is beneficial. It should be noted that many VBE systems make use of lead screws that have lower pitch and rely on friction to hold their displacement. In terms of implications of our results on different mission profiles, in situations where the proportion of buoyancy change manoeuvres is equally distributed between shallow and near design depths, (e.g., Gliders, Floats), neither pre-tensioned designs or traditional non-pretensioned VBE designs tested in this work have a definite advantage over the other. For missions such as those of seafloor mapping AUVs, or Lagrangian imaging floats, which typically dive and perform depth control manoeuvres at large water depths, the reversed energy-depth relationship of the proposed pre-tensioning can improve energy efficiency over non-pretensioned systems.

V. Conclusion

This paper demonstrates that pre-tensioning of VBEs using springs can achieve fail-safe behaviour and improve energy efficiency compared to traditional VBEs when operating below a certain depth. Our comparison of O-ring and bellows based piston sealing shows that a larger recovery of buoyancy can be achieved by fail-safe behaviour with the bellows sealed configuration, though accounting for internal frictions in the design stage to increase the pre-tensioning effect would allow for full buoyancy recovery with both designs. The O-ring sealed configuration is more energy efficient due to internal friction reducing the torque needed from the actuator to hold a static position.

Whilst key operational characteristics of pre-tensioned VBEs have been identified and the design response understood, there is still more research needed to optimise the design variables. One such variable is the amount that the springs should pre-tensioned by at the piston's maximum and minimum displacement. Having a larger degree of compression in the springs when the system is at maximum displacement would allow for small residual forces such as those due to internal and sealing friction to be overcome. However, this would come at the cost of the maximum achievable displacement change for a given spring and piston setup. The second variable is the type of lead screw to use. Reducing the pitch of the screw thread would improve the energy efficiency of the system, which is currently dominated by the holding torque requirement. However, this also means that fail-safe behaviour would only be possible with springs sized to overcome the increased friction of the system. Further investigation and testing is needed to understand these design tradeoffs more completely.

Finally, although the current prototype is a promising proof of concept of the pre-tensioned VBE design, the setup has only been tested with a small rated design depth compared to what is expected by operational AUVs, which can work thousands of metres below the surface. Key challenges to scale up to higher rated depths will involve generating a pre-tensioning force high enough to overcome the high pressures at these depths, and having a means of reducing water displacement against these springs. It should be noted that these forces would be no greater than the forces currently experienced by VBE systems when they operate at depth, however, methods to benefit from gearing ratios, and non-linear mechanism to mechanically store potential energy are thought to be necessary for depths beyond a few hundred metres.

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