Optimal Thrust Characteristics of a Synthetic Jet Actuator for Application in Low Speed Maneuvering of Underwater Vehicles

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Abstract— **Compact zero-mass pulsatile jet actuators are proposed for low speed maneuvering and station keeping of small underwater vehicles. The flow field of such jets are initially dominated by vortex ring formation. Prototypes of such actuators are built and tested. The current actuator design has a mechanical plunger system to generate pulsatile jets, whose oscillation frequency is varied between zero and 40 Hz. This actuator is designed so that the cavity dimensions, exit diameter, actuation frequency, and actuation profile can be easily varied in order to find the optimal operation point of the actuator. Thrust measurement data is provided for various formation numbers while the actuation frequency in varied. The empirical thrust profiles were seen to follow the same trend as a model previously developed by our group. It is also observed that the measured thrust has a maximum value for formation numbers between 4 and 5.5, which is in agreement with our model. These optimal parameters will be used as design constraints for future actuators used in underwater propulsion.**

I. Introduction

Marine excavation (especially deep sea excursion) has taken great strides recently with the advent of advanced sensing techniques as well as highly controllable remotely operated vehicles (ROVs). Most ROV's need significant logistic support, such as escort ships, that could limit their availability to the general research community. Furthermore, the required cable connection has limiting effects on ROV's operation, in particular in deep oceans. Ultimately, as these vehicles requirements become increasingly demanding, their limitations will become mission critical. Therefore, self-propelled autonomous underwater vehicles (AUVs) will become increasingly important in the commercial realm. Such autonomous vehicles are expected to require less technical and logistic support, and will be capable of operating in regions into which no manned underwater vessel or ROV could penetrate (e.g., below the ice regions).

Hydrodynamic design of AUVs are often driven on a few competing fronts: (i) Rapid and efficient deployment to the work-zone and (ii) low speed maneuvering during the docking procedure and for operations at the work-zone. Rapid deployment necessitates a streamlined body of revolution (*e.g.* Torpedo-shape design) for fast cruising with minimal energy. However, since the trajectory of this type of vehicles is adjusted using control surfaces, the magnitude of the available control force is proportional to the vehicle's speed. Consequently, these vehicles are difficult to maneuver at low speeds and in tight spaces. Therefore, they are difficult to dock or maneuver through sunken excavation sites. Such vehicles also cannot opportunistically enter a precise loitering or hovering mode. As a result much current effort is devoted to the development of docking mechanisms, but this is just a solution for the symptoms, and doesn't really address the problem of the vehicle's actual maneuvering capabilities.

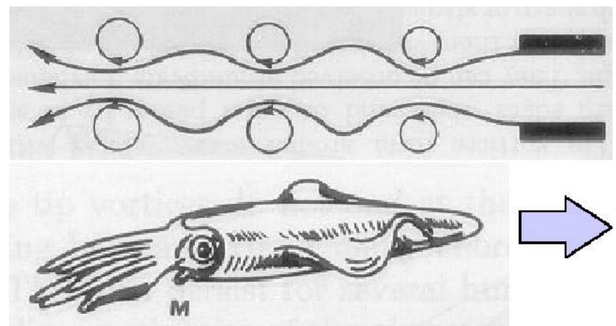


Fig. 1. Squid locomotion by pulsed jet.

On the other hand, low speed maneuvering and better control are often achieved by the so-called box-design where the low drag body-of-revolution design is sacrificed by adding multiple thrusters at different locations and directions. In this case, precise maneuvering can be achieved at the cost of increased drag and the need for an alternate technique to transport the vehicle from the offshore base or an escort ship to the work-zone.

In an effort to resolve this trade-off, recent proposals have been made to use compact synthetic jets for low speed maneuvering or locomotion of small unmanned underwater vehicles (UUVs) [1], [2]. The propulsion scheme suggested here is loosely inspired by the propulsion of cephalopods and jellyfish [3], [4], [5], [6], [7], [8]. Squid (see figure 1) use a combination of fin undulations and a jet which can direct thrust at any angle through a hemisphere below the body plane. Jet locomotion of the squid is accomplished by drawing water into the mantle cavity, and then contracting the mantle muscles to force water out through the funnel. The funnel, which is directly behind and slightly below the head, can be maneuvered so as to direct jets in a wide range of directions. Since nature has had thousands of years to optimize this actuation technique, these basic parameters are an ideal

Fig. 2. Cylinder piston mechanism.

starting position for our own optimization. Another example of pulsatile jet locomotion is jellyfish swimming [9], which relies upon repeated contractions of an umbrella-shaped structure, or bell. This bell cavity has the unique ability to modify its volume and control jet geometry during undulation which will define the direction of future research.

Weihs [8], Seikman [6], and recently Krueger and Gharib [10] have shown that a pulsed jet can give rise to a greater average thrust force than a steady jet of equivalent mass flow rate. In a pulsed jet, an ejected mass of fluid rolls into a toroidal vortex ring which moves away from its source. A continuously pulsed jet, therefore, produces a row of vortex rings (see Figure 1). At high pulsing frequency, the jet structure can become increasingly turbulent.

This manuscript considers thrust characteristics of a synthetic jet actuator (see Figure 3) for application in underwater vehicle locomotion and maneuvering. A Cylinder-piston mechanism was traditionally used for starting jets. This system provides a simplified approximation to natural pulsatile jet generation, and is amenable to experimental, computational, and analytic study. A starting jet is usually characterized by the roll up of the ejected shear layer from a nozzle or an orifice and the formation of vortex rings. The generation, formation, evolution, and interactions of vortex rings have been the subject of numerous investigations (see, *e.g.* Shariff and Leonard [11] and the references in there). In this study, we focus our attention on a specific characteristic of vortex ring formation; namely the impulse extremization in vortex ring formation and its connection with the vortex ring pinch-off phenomenon.

A variety of mechanical drivers can be employed to oscillate the pressure within a cavity necessary to generate vortex ring jets. A cylindrical cavity can be contracted and expanded changing its volume very similar to biological methods. However, a much simpler design would keep a constant sized cavity and use an internal piston to drive the pressure variations; the so-called cylinder-piston mechanism (see Figure 2). When the piston pushes fluid through the cylinder, the boundary layer of the fluid expelled from the cylinder will separate and roll up into a vortex ring at the orifice edge. Experiments [12] have shown that for large enough ratios of piston stroke versus diameter (L/D), the generated flow consists of a leading vortex ring followed by a trailing jet.

While the piston-cylinder model is attractive for theoretical studies and ease of experimental set-up, there are more practical means to generate pulsatile jets. To this end, prototypes of pulsatile jet generators using the Helmholtz cavity concept are designed and built [13], [14]. Various techniques can be employed for actuating the diaphragm. These includes, but are not limited to, using electromagnetic actuations (*e.g.* solenoid plungers), electrostatic and piezoelectric actuation. In this design the inward movement of a diaphragm draws fluid into a chamber (Figure 3). The subsequent outward diaphragm

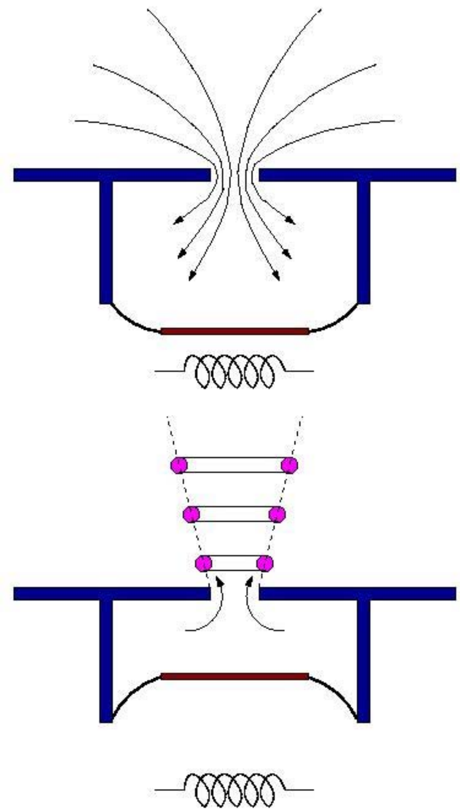
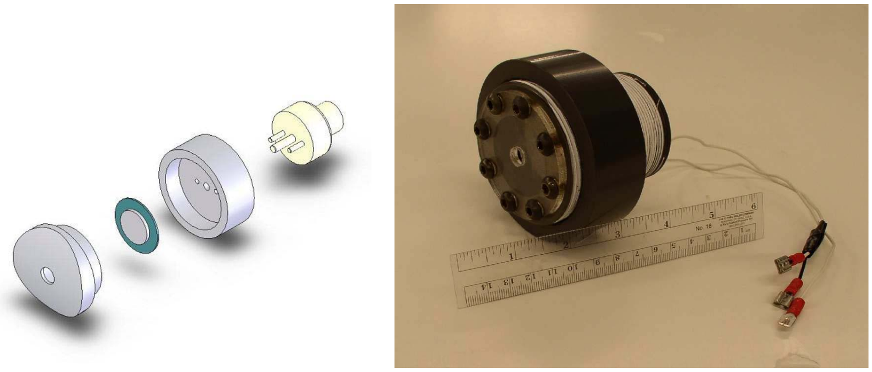


Fig. 3. Synthetic jet actuator concept: (Top) Fluid entrainment; (Bottom) vortex ring formation.

movement expels the fluid, forming a vortex ring or a jet depending on the formation number. Repetition of this cycle results in a pulsatile jet. Because of the asymmetry of the flow during the inflow and outflow phases, a net fluid impulse is generated in each cycle, even though there is no net mass flow through the chamber over one cycle. For a more in depth consideration of the net mass and momentum flux in this regime see Mittal *et al.* [15].

Figure 4 shows the structure and appearance of a pulsatile jet actuator prototype [13], [14]. The driving diaphragms consist of a rigid disk with a flexible surround. The diaphragm can be actuated by electrical, mechanical, or magnetic actuations. Currently a solenoid actuator is used to generate the diaphragm motion. The fluid pushed by the moving diaphragm exits through an orifice. Ultimately the optimal parameters discovered in this research will drive the design constraints on this prototype for use in AUV maneuvering. This design has many advantages including its simplicity, very few moving parts, and compactness.

Mohseni [1], [2] offered a model to predict the impulse of



(a) (b)

Fig. 4. CU Boulder Synthetic jet prototype [13], [14]: (a) Plunger and solenoid assembly. (b) Actual fabrication of the synthetic jet actuator.

vortex ring jets with varying parameters in a synthetic jet. This investigation is focused on direct measurement of thrust in a synthetic jet while the actuation frequency and the formation numbers are varied. Remotely controlled underwater vehicles designed to incorporate these actuators, and prove their ability to provide control forces have been built and tested at the University of Colorado at Boulder. Two such vehicles are shown in the following figure.

The newer vehicle, known as the Remote Aquatic Vehicle (RAV), houses four Synthetic Jet Actuators (SJA's). The actuators used in the RAV produce thrust with a solenoid type of actuation. An exploded view of the actuator is shown in the following figure. Acoustic actuation was also recently explored in [16].

II. Experimental Setup

Schematic of the thrust measurement system is shown in Figure 6. The actuator is submerged in large tank of water (weighted to be neutrally buoyant) and suspended by a plate which restricts all horizontal motion. The vertical motion was driven by the vortex jet impulse transfer, and measured by a load cell mounted on the plate, in contact with the actuator.

The actuator itself is driven by a mechanical plunger system. The motor's rotational motion is translated to a linear oscillation through a cam mechanism. The plunger consists of a cylindrical accordion shaped bellows, which oscillates up and down inside the Helmholtz cavity. Though solenoid-diaphragm actuation systems have many benefits in vehicle applications (mainly due to their compact size), we found that a better controlled experiment can be conducted with our mechanical plunger driven by a motor. In an optimization process it is necessary to maintain close controls, in order to accurately observe the effect of parameter variation. It was in this respect that a mechanical plunger system was found useful. For example the main focus of our experiment was to quantify the effect of adjusting the formation number of the expelled jet. In order to accomplish this a very accurate control of the formation number is required. If the jet volume were to remain constant, the control over the formation geometry would be a simple matter of adjusting the orifice diameter. With a solenoid setup the deflection of the diaphragm is a function of the load, causing the jet volume to vary with frequency. The mechanical plunger; however, has a stroke length completely determined by the geometry of the cam, allowing for a constant volume and easily controllable formation number. Additionally the mechanical plunger setup allows the piston to be placed in Helmholtz cavities of any geometry, allowing even greater control over the design parameters during experimentation. Once the optimal characteristics have been determined they can then be adapted to a simpler solenoid design, which has more benefits in vehicular application.

This entire mechanical system was placed in a PVC canister (to make it water tight) and submerged in the water tank. The setup was used to acquire two sets of data; the first is the actual thrust output from the actuator which is processed by the computer from the load cell voltage output. The second is the rotation frequency of the motor which is processed by the computer from the motor encoder pulse count, translated and filtered through an HP universal counter.

III. Results and Discussion

The described setup in Figure 6 was then driven at various test conditions. The orifice was adjusted such that the formation number (L/D) varied between 2 and 8 (with higher sensitivity around L/D of 4, the theoretical optimum). This parameter could be easily controlled since a mechanical plunger system forces the jets to maintain a constant volume. For each formation number the motor was adjusted to run between frequencies of 0 and 40 Hz. Each arrangement generated a thrust response curve in the time domain. It should be noted that the response curve is comprised of several smaller waveforms each containing 300 thrust samples for a single oscillation frequency value. The sum of these waves over the entire frequency domain of the experiment represents a complete description of the specific formation number's response. Two examples of these smaller waveforms (taken with a formation number 3.93) are depicted in Figures 8 and 9.

The thrust curve can be seen to have an average thrust value above the offset; in fact at higher frequencies the entire curve

Fig. 5. University of Colorado Test Beds

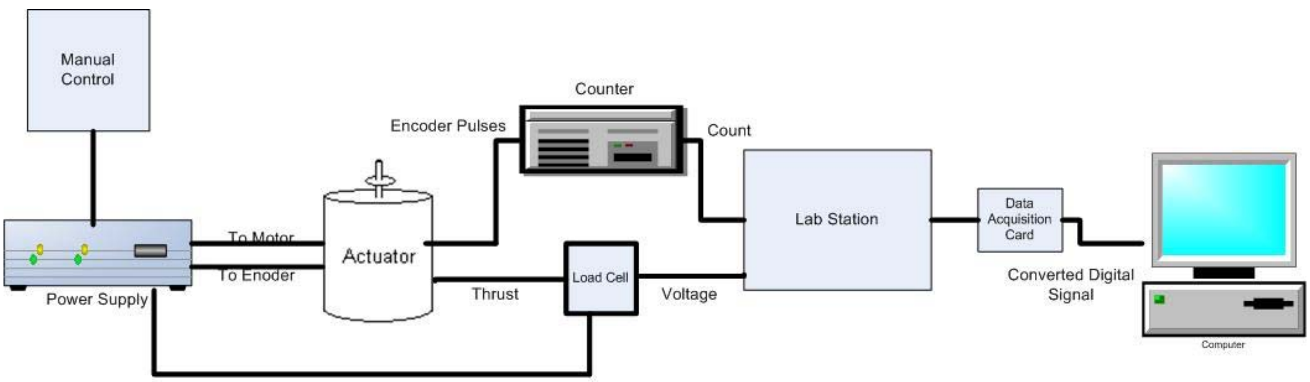
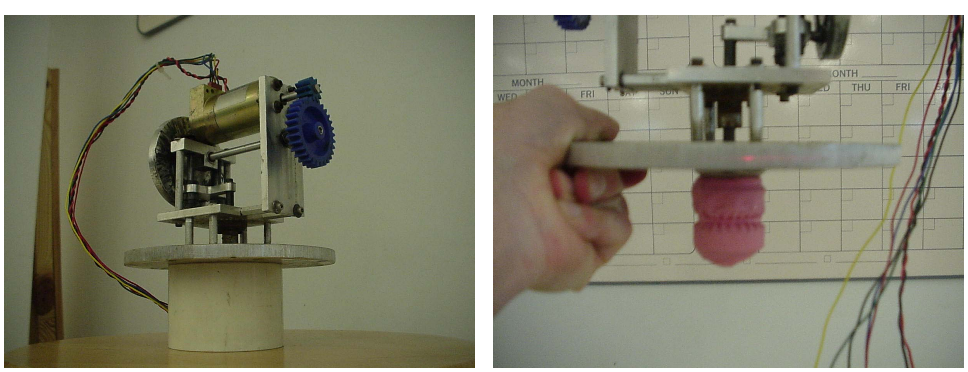


Fig. 6. Schematic of the experimental setup.



(a) (b)

Fig. 7. Mechanical plunger setup (a) motor, gear and cam assembly. (b) Piston/plunger inside the cavity.

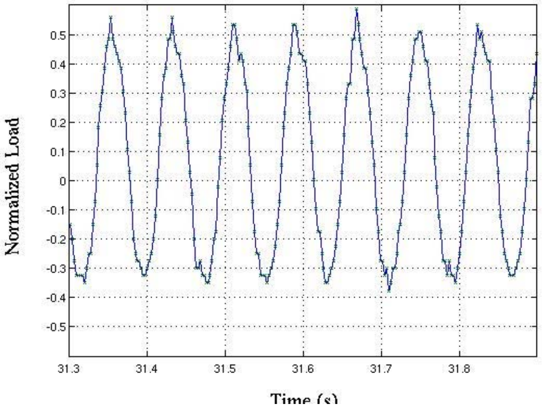


Fig. 8. Normalized load at 11 Hz actuation.

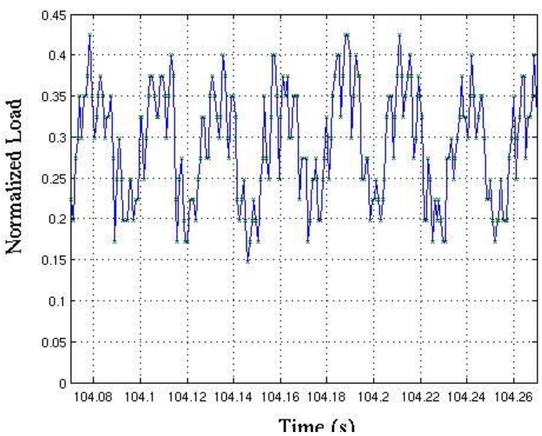


Fig. 9. Normalized load at 40 Hz actuation.

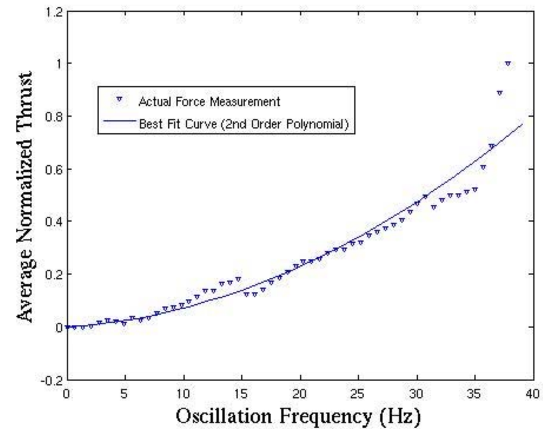


Fig. 10. Actuator thrust response (symbols) and fitted curve (solid line) in the frequency domain for $L/D = 3.93$.

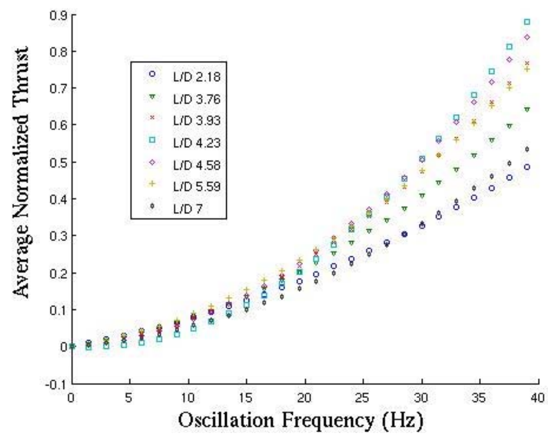


Fig. 11. Curve fitted actuator thrust response in the frequency domain for various formation numbers.

is above the offset, verifying the ability of the actuator to create a sustainable thrust. Each of these single frequency sections can then be averaged to find a mean, sustainable thrust pertaining to the section's specific oscillation frequency. Using this type of analysis, the thrust response curve can be depicted in the frequency domain rather than the time domain, which is much more relevant to the optimization of the actuator. In an effort to incorporate the forces lost to dynamic effects an inertia correction factor was calculated and included to take into account the acceleration of our system. One thrust response curve in the frequency domain is shown in Figure 10 for $L/D = 3.93$. As predicted in Mohseni [1], [2] the expected thrust shows dependency to the square of the actuation frequency. A second order polynomial fit to the experimental data is also shown in Figure 10. Fitted curves to the experimental data for other formation numbers are shown in Figure 11, where the same dependency on frequency is observed. It is clearly seen that the maximum thrust at most frequencies is achieved for formation numbers around 4-5.

Figure 11 is useful in recognizing the response of the actuator due to increased frequency, but it is difficult to discern the dependence of thrust with respect to the formation number. In that regard the same data has been re-plotted in Figure 12 on the formation number domain with each line pertaining to a specific frequency. This figure demonstrates that the optimum formation number is achieved around 4-5.5, which is in reasonable agreement with our model [1], [2]. As seen in this Figure the thrust value drops off rapidly as the jet deviates from the optimal value.

IV. Conclusion and Future Work

Thrust characteristics of a synthetic jet actuator for applications in underwater vehicles were studied. A new synthetic jet actuator was designed and built in order to easily control the actuation frequency, profile and cavity geometry. As predicted by our theoretical model, the empirical thrust shows a square dependency on the actuation frequency. It is observed that the measured thrust achieves a maximum value for formation numbers between 4 and 5.5, which is in agreement with our model. Future studies include investigation on the effect

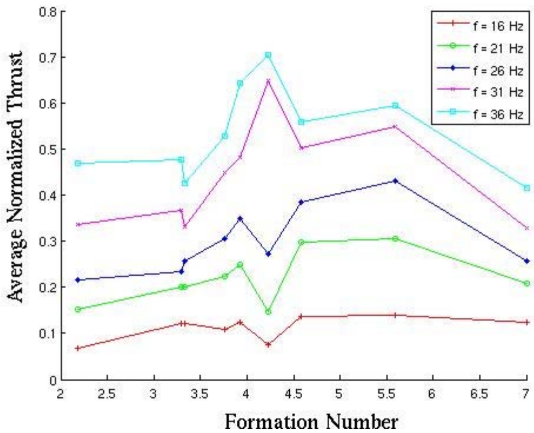


Fig. 12. Averaged normalized actuator trust response in formation number domain.

of design parameters such as the plunger stroke profile and cavity dimensions on the thrust generated, thus giving a scope for an optimal actuator design. Pulsatile jet actuators are especially applicable in low speed maneuvering of underwater vehicles where precision maneuvering is required, while still maintaining a low drag body of revolution.

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