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DESIGN OF HIGH PRESSURE WATERJET NOZZLES

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Introduction

The Hydroblast Research Cell at Marshall Space Flight Center is used to investigate the use of high pressure waterjets to strip paint, grease, adhesive and thermal spray coatings from various substrates. Current methods of cleaning often use ozone depleting chemicals (ODC) such as chlorinated solvents. High pressure waterjet cleaning has proven to be a viable alternative to the use of solvents [4, 5]. A popular method of waterjet cleaning involves the use of a rotating, multijet, high pressure water nozzle which is robotically controlled. This method enables rapid cleaning of a large area, but problems such as incomplete coverage (e.g. the formation of "islands" of material not cleaned) and damage to the substrate from the waterjet have been observed.

This report summarizes research conducted by the author as a Summer Faculty Fellow at MSFC in 1994. The project consisted of identifying and investigating the basic properties of rotating, multijet, high pressure water nozzles, and how particular designs and modes of operation affect such things as stripping rate, standoff distance and completeness of coverage. The study involved computer simulations, an extensive literature review, and experimental studies of different nozzle designs.

Definitions

Since there is no widespread convention regarding terminology of waterjet production, we define here the terms used in this paper: **target:** object upon which waterjet impinges, **substrate:** material to be cleaned, usually coated with paint, grease or other material which needs to be removed via waterjet, **coating:** generic name for material to be removed from substrate, **nozzle:** device for delivering high pressure waterjets to target - is usually attached to a robotic arm, **orifice:** final exit device for waterjet – there are several orifices on a single multijet nozzle, **orifice configuration:** placement of orifices on surface of nozzle, **orifice geometry:** the internal structure of an individual orifice, **sweep rate:** rate at which nozzle is moved parallel to the target, or target is moved past nozzle (as is the case when the target is on a rotating turntable), **nozzle angular velocity:** rate at which nozzle rotates, **standoff distance:** distance from nozzle to target, **islands:** regions of the target where the coating has not been removed from the substrate after waterjet cleaning, **dwell time:** the amount of time a waterjet is in continuous contact with a particular region of the target, **stripping width:** width of the cleaning path as the nozzle is moved over the target.

Factors Affecting Waterjet Cleaning Requirements

Of paramount concern in waterjet cleaning is maintaining the integrity of the substrate. Thus, for a particular material, we need to know the effect of standoff distance, water pressure and dwell time on the substrate to be cleaned and the coating to be removed. This information is not the focus of this paper and hence will be assumed to be known, either through theory, or more likely, through experiment. Given this information, standoff distance, water pressure and dwell time can be adjusted so that the coating is removed and the substrate is not damaged. The impact of the water on the target increases with increases in pressure and dwell time and decreases with increased standoff distance. It may be necessary to make several passes over the target in order to remove the coating without damaging the substrate. This can also be accomplished via overlap from multiple jets.

Another important constraint is the time required to clean the target. This will be a function of the stripping width, the sweep rate and the number of passes necessary for cleaning.

Standoff distance will be constrained by the geometry of the target. For a perfectly flat plate, there is no constraint on possible standoff distance. If there are protrusions, however, such as bolts or ridges, then this will limit the possible standoff distances, unless the robot to which the nozzle is attached is equipped with the means to adjust to variations in the target geometry.

Factors Affecting Waterjet Cleaning Performance

To maximize waterjet cleaning performance, it desirable to have complete coverage, i.e. to eliminate the production of coating "islands", and have the largest possible standoff distance. The coverage aspect of waterjet cleaning will be a function of the orifice configuration. The standoff distance will be a function of the compactness of the jet issuing from each orifice. Jet compactness is determined by the way in which the water is delivered to the individual orifices, and the internal geometry of each orifice.

Coverage

The main factors affecting coverage are the number of orifices and the placement of these orifices on the nozzle.

The angular velocity of the nozzle necessary for full coverage goes down as the number of orifices increases. However, since there is a maximum flow rate associated with each pump, there is a limit to the number of orifices that can be added. (In theory, an unlimited number of orifices can be added by simply decreasing the exit diameter of each orifice, but manufacturing considerations place a lower limit on the diameter of the orifice.) Below, we derive a formula for the maximum number of orifices that can be placed on a nozzle for a given flow rate, pressure and orifice exit diameter. Let F = flow rate, A = cross sectional area of orifice exit, v = exit velocity of waterjet, d = exit diameter of orifice, p = pump pressure, p_a = atmospheric pressure, ρ = density of water and n = number of orifices. Then $F = nvA$. But $A = \pi d^2/4$ and from a modification of Bernoulli's law we have $v = c_\nu\sqrt{\frac{2(p-p_a)}{\rho}}$, where c_ν is an experimentally determined constant called the velocity coefficient which is usually between 0.9 and 0.95 [4]. So, $n \leq \frac{4F}{\pi d^2}\sqrt{\frac{\rho}{2(p-p_a)}}$. For a conservative assessment of n, we set $c_\nu = 1$. Thus if $F = 13$ gpm $= 50\text{in}^3/\text{sec}$, $p = 36,000$ psi, and $d = .019$in, we have $n \leq 6.36$ (i.e. $n \leq 6$). Once the number of orifices for the nozzle is chosen, the effect of different placements can be studied.

In studying the effect of orifice placement, we consider the path traced by each orifice as the nozzle rotates and translates. We label the orifices $i = 1, \ldots, n$ and denote their positions by radial distance from the center, r_i, and angular position on the nozzle, φ_i, as shown in Fig.1a. Then the path traced out by each orifice is given by the set of parametric equations $\{x = v_0 t + r_i \cos(\omega t + \varphi_i + \varphi_0), y = r_i \sin(\omega t + \varphi_i + \varphi_0)\}$ where v_0 is the sweep rate, ω is the angular velocity of the nozzle and φ_0 is the angular displacement of the line from the center of the nozzle to orifice number 1 from the x axis at $t = 0$. Fig.1b shows the path traced out by a single orifice over one complete rotation of the nozzle. It can be seen from this figure that the trace assumes a roughly circular shape. It then seems reasonable to try and design a system such that the "circle" traced by each orifice lies exactly one trace width to the right of the "circle" traced by the preceding orifice. (The trace width will be determined by the jet shape and standoff distance.)

One way to accomplish this is to arrange the orifices at an equal distance from the center of the nozzle with equal angular spacing. Then, if the minimum trace width of all the orifices is denoted by w_t, sweep rate and angular velocity must satisfy the relation $\omega \geq \frac{2\pi v_0}{n w_t}$ if we are to have complete coverage [4]. For example, if $n = 6$, $w_t = 0.5$ mm and $v_0 = 30$ mm, then we require $\omega \geq 20\pi$ for complete coverage. Fig.2a shows the trace of a single orifice (for $\omega = 20\pi$) and Fig.2b shows the trace of the complete nozzle and demonstrates that complete coverage is achieved. Note that each point on the target is actually hit at least twice, once by the "right" half of a "circle", and once by the "left" half of a "circle". Points at the top and bottom of the path will be hit several times, with the exact number dependent upon the shape and dimensions of the trace. Increasing ω, or decreasing v_0, will increase the amount of overlap and hence the number of times each point on the target will be hit by a waterjet.

Many existing rotary nozzles have orifices placed at various radial distances from the center of the nozzle. If we take, for example, $r_1 = 7, r_2 = 14, r_3 = 21, r_4 = 28, r_5 = 35, r_6 = 42$ (millimeters), we can see that each nozzle will trace out a band of height $h_1 = 14, h_2 = 28, \ldots h_6 = 84$ (millimeters). Combining these in Fig.3 for the same v_0 and ω as for the nozzle whose trace is depicted in Fig.2b, we see that the nozzle will trace out a pattern which leaves many coating "islands" where water does not hit the target. This has been observed in hydroblast operations at MSFC. Thus a nozzle with orifices all at an equal distance from the center of the nozzle with equal angular spacing gives superior coverage compared to a nozzle whose orifices are arranged at unequal distances from the center. The latter nozzle design would be more appropriate for applications such as rock drilling, where it is desirable to have more energy delivered to the center of the target than at the edges.

The preceding analysis assumes that all of the orifices emit jets that travel parallel to the centerline of the nozzle and that the centerline is aligned perpendicular to the target which is assumed flat. If the nozzles are slanted with respect to the nozzle and the nozzle is slanted with respect to the target (as shown in Fig.4), then the trace width will vary over each complete revolution of the nozzle. A precise characterization of the jet shape is thus necessary to determine what the trace will be. The jet shape is a primarily a function of the orifice geometry and the water pressure, as is discussed below. We note here that the influence of gravity on the jet must also be accounted for, although this effect will be negligible for short jets.

Water Delivery System

In order to have a jet stream which can travel a long distance before breaking up, it is necessary to have a non-turbulent flow delivered to the orifices. Therefore, the channel which delivers the water to the orifices should be designed so that bends (especially right angles) are minimized.

Orifice Geometry and Jet Compactness

A liquid jet issuing into the air has a structure [4] which consists of a core surrounded be a layer of droplets (Fig.5). Increasing the core length increases the standoff distance we can use in cleaning operations. We call the region of the jet which contains a core the "compact" region of the jet. Many papers have studied the effect of various orifice designs on jet compactness [1–3, 6]. Once a basic shape for the internal profile of the orifice is chosen, one can attempt to maximize the core length of the jet produced by varying the internal parameters of the orifice. For this study, two basic orifice geometries (see Figs.6a and 6b) were selected after a thorough literature search for orifice designs which yield highly compact jets. To start the process of optimizing these designs, it was decided that the effect of various L/D ratios on jet compactness would be studied experimentally. The method chosen for evaluating the nozzles was high speed video imaging. At the time of completion of this report, manufacture of the nozzles was not complete, so test results will have to be presented in a future report.

Summary

Basic properties of rotating, multijet, high pressure water nozzles have been outlined. An orifice configuration which enables complete coverage during cleaning has been identified. Orifice geometries likely to produce highly compact jets have been presented. Various orifice configurations will be tested and the results presented in a future report.

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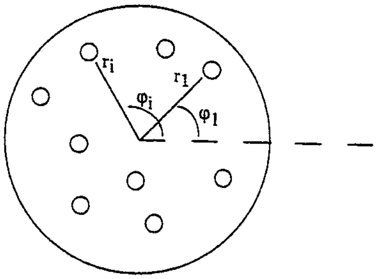

Fig. 1a

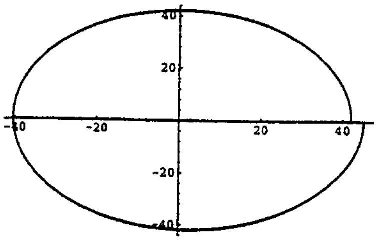

Fig. 1b

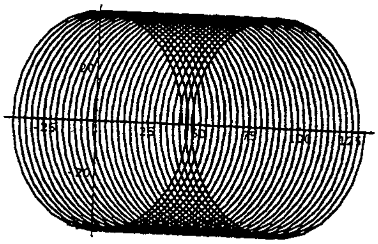

Fig. 2a

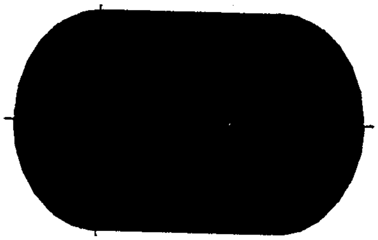

Fig. 2b

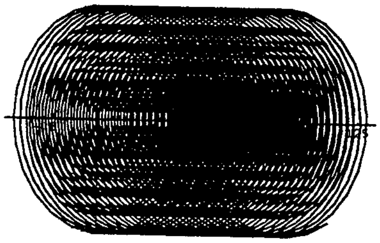

Fig. 3

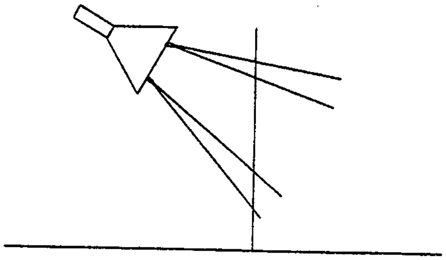

Fig. 4

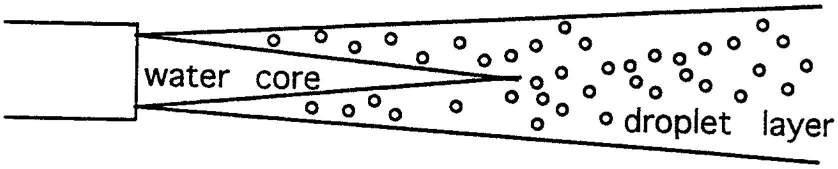

Fig. 5

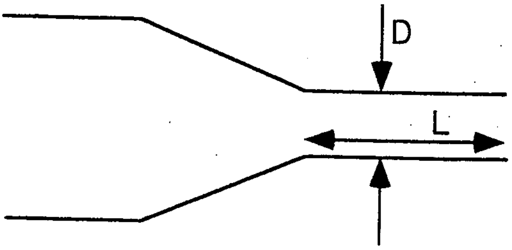

Fig. 6a

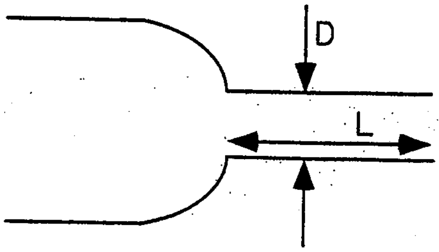

Fig. 6b