CLEANING AND CUTTING WITH SELF-RESONATING PULSED WATER JETS

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ABSTRACT

A new type of pulsed water jet, which uses principles of self-resonance to create pressure fluctuations, is now being developed. The advantages of pulsing to improve the erosive action of a jet—by interrupting the flow, hence using the water hammer impact stress created by each individual slug—have long been appreciated by the users of water jets for cutting and cleaning applications. Of several self-resonating pulsed jet, or "SERVOJET", concepts, a design incorporating a Helmholtz resonating chamber, tuned to drive an organ-pipe segment, has proven feasible for in-air interruption of a water jet. Experimental results for several cleaning and cutting applications are described.

INTRODUCTION

Motivation

The increased erosivity afforded by causing a water jet to break up into a series of water slugs has long been recognized. Such interrupted or pulsed jets offer the following advantages, relative to steady-flowing jets, for either cleaning a substance from a substrate or cutting into a bulk material such as a rock:

1. Larger impact stresses, due to the water hammer pressure, which enhance the local erosive intensity,
2. Larger outflow velocities across the surface being cleaned (or cut) thus providing an increased washing action, (or opening cracks and flaws in a bulk material for cutting applications),
3. Greater ratio of impacted area per volume of jetted water, thus exposing larger areas of the surface to the water hammer pressure,
4. Cycling of loading; this promotes unloading stresses which may enhance the process of de-bonding the substance from the substrate, or fracturing the bulk material being cut, and
5. Short duration loadings, which tend to minimize energy losses within either the substrate being cleaned or the bulk material being cut, and hence increase the material removed per input energy.

A variety of mechanical techniques have been used to interrupt water jets. There have been external, rotating disks containing slots, holes, or sprockets (Summers (1975), Lichtarowicz and Nwachukwu (1978), Erdmann-Jesnitzer, et al. (1980)); an internal, spinning slotted rotor (Nebeker (1981); and an internal, piezoelectric transducer (Danel and Guilloud (1974)). Although each of these methods produced a series of water slugs—and improved erosion relative to steady jets was consistently observed—the frequency of interruption was always well below optimum as discussed below. Also, the complexity and short component life-times associated with these mechanical methods has prevented the development of a practical, high-pressure interrupted water jet system. The possibility of achieving very high frequencies of jet pulsation—with no moving parts—motivated the ongoing effort to learn how to create self-resonating nozzle systems, as described in this paper.

Background

The original impetus for development of a self-resonating nozzle arose from the need to create improved submerged cavitating jets to augment the action of deep-hole drill bits. Although it had been shown that 'conventional (i.e., non-resonating) cavitating jets could provide improved rates of drilling (Conn, et al., (1981))the cavitation inception limit of such jets (about 1,220 m (4,000 ft) depth with a nozzle pressure drop of 13.8 MPa (2,000 psi)) led to a search for some means to cause jet cavitation at greater depths. Several self-resonating nozzle design concepts were developed, which proved capable of achieving the goal of enhanced cavitation at greater depths (Johnson, et al., (1982a, b, and c)). Labeled "STRATOJET" (STRuctured Acoustically Tuned Oscillating JET), these new nozzle systems caused cavitation to be attained to depths two to six times deeper than conventional drill bit nozzles.

Three self-resonating nozzle system concepts are shown schematically in Figure 1; detailed descriptions of the performance of each of these concepts can be found in the references cited above. As described in the next section, the "PULSER-FED" self-resonating nozzle system (Figure 1c) has proven to be an effective design for producing high frequency interruptions of a water jet operated in air. This design, to be hereafter termed the "SERVOJET" (SelfExcited Ring-Vortex, Organized JET), was used in the experiments to be discussed, which have shown that high frequency jet pulsations can indeed improve the performance of an in-air cleaning or cutting water jet.

A non-dimensional parameter which defines the periodic characteristics of any oscillating system is the Strouhal number, Sd. For jets:

$$Sd = fd/V,$$

where:

f is the resonating frequency;
d and V are, respectively, the jet diameter and velocity.

Preliminary analyses of the characteristics of in-air pulsed jets (Chahine, et al. (1982a, 1982b, and 1983)) have shown that optimum performance of such jets should occur for Strouhal numbers in the range: $0 3 < Sd \leq 1.2$. The criteria evaluated were: (1) relaxation of the impulsive stress created by each slug, (2) cushioning of the stress by a liquid layer from the previous slug, and (3) aerodynamic effects causing slug disintegration. Although the optimum Sd-range can readily be achieved within a passive self-resonating system, all of the mechanical jet-interruption systems cited previously were operated at frequencies which produced Sd values well below the optimum range. In each of these mechanical system studies, where frequency variations were made—increases in the interruption rate always produced improvements in erosivity.

This trend of increased pulsed jet erosiveness with frequencies that tended to approach the optimum range was an additional encouragement for our attempt to adapt the submerged self-resonating ideas to the interruption of a water jet operated in air.

SELF-RESONATING JET CONCEPTS

The "PULSER-FED" self-resonating jet (SERVOJET) shown in Figure 1c, was the concept found to be most readily adaptable to creating an in-air pulsed jet. It can be seen from the several configurations in Figure 1 that the PULSER-FED concept is a combination of the I^PULSERII (Figure la) and "ORGAN PIPE" (Figure lb) configurations. A tandem-orifice Helmholtz resonating chamber (diameter, dT, in Figure 1c), is tuned so as to excite a standing wave within the organ-pipe section (length, Lp, Figure 1c). Peak resonance in this system occurs when the frequencies of the Helmholtz chamber and the organ-pipe wave are matched to a preferred jet structuring frequency for the exit orifice (de in Figure 1c). By varying the several dimensions of this system and the operating pressure, first, second, or third mode resonances can be selected. See Chahine, et al. (1982a, 1982b, and 1983) for further details on the performance of these selfresonating systems.

EXPERIMENTAL PROCEDURES

To learn how to create a self-resonating pulsed jet, it was first necessary to develop ways of quantifying their performance. Several techniques were used, as indicated in Figure 2, to measure the pressure and flow fluctuations in these jets. There were: (1) pressure transducers in the organ-pipe segment of the nozzle and (2) in a target plate which could be located at various standoff distances, X, away from the nozzle, (3) a laser beam, shone through the jet so as to impinge upon a photo multiplier tube, and (4) single flash and high-speed photography.

Good agreement was observed amongst the frequency spectra measured with each of these techniques. Typical correlations are seen in Figure 3, where the pressure fluctuations in the organ-pipe section of the SERVOJET nozzle (lowest trace) are compared with target plate pressures measured at several standoff distances. These pressure fluctuations, p', have been normalized by the pressure drop across the nozzle, Δp. The principal frequency for this test occurred at f 5.5 kHz (Sd 0.38), with a subharmonic at f = 3.1 kHz (Sd = 0.20), and second and third harmonics at about 11 and 16.5 kHz. These spectra are seen, with varying amplitudes of the fluctuations, at each measuring location. Note, for instance, that the subharmonic - which is well defined inside the pipe - is very weakly seen in the pulsed jet as it strikes the target. Conversely, the second and third harmonics - quite small in the pipe - are strongly amplified in the jet, particulary at X = 17.8 cm (7 in.) (X/d - 38), the optimum standoff distance for this jet at this velocity. At X = 17.8 cm, the target plate fluctuations were 10 percent, for in pipe fluctuations of only 2.5 percent. Similar correlations were also observed between the laser beam interruption measurements and the pressure fluctuations.

Several high-speed movies were taken, using a HYCAM camera. The best photographic results, however, were achieved by single flash lighting, using a MAMIYA camera and Kodax 4X black and white film. Several typical photographs are seen in

Figure 4, for ap values ranging from about 3.4 to 4.5 MPa (500 to 650 psi). Although such photographs were successfully taken for pressures up to about 6.2 MPa (900 psi), it was necessary to rely on the pressure fluctuation measurements for higher pressures. Tests up to 62 MPa (9,000 psi) have been performed with SERVOJET nozzles; with nozzle orifice diameters ranging from 2.2 to 4.7 mm (0.085 to 0.185 in.).

EXPERIMENTAL RESULTS

Since the SERVOJET nozzle concept is actively under development, extensive evaluations are still to be performed. Several preliminary and feasibility studies have been conducted, however, and some of these results will be described in the following sections. In each case, tests were conducted by causing the jet to pass in a straight line, at a constant velocity, across the target.

Paint Removal

During a feasibility study supported by the Office of Naval Research[1], Chahine, et al. (1982b) showed that a passively interrupted jet could provide enhanced rates of removal of paint layers from both aluminum and graphite reinforced epoxy panels. Comparative runs were made between SERVOJET nozzles and a Leach and Walker (1966) nozzle, to determine whether the pulsed jet could be used to remove successive paint layers without damaging the substrate, thus providing an alternative to the chemical stripping methods now used on aircraft. Also, since chemicals cannot be used on the composite segments which are being installed at an accelerated pace on these airplanes - some sort of mechanical paint removal alternative is now being urgently sought.

The preliminary results from this study were encouraging, but it must be emphasized that considerable work remains to be done before a viable pulsed jet aircraft paint stripping system is available. In comparison to the Leach and Walker (L&W) nozzle the SERVOJET created a consistently wider, more uniform cleared path. Some typical results are shown in Figure 5 for the removal of various paint layers from an aluminum aircraft panel. This panel had three MILSPEC polyurethane-based coats above a yellow epoxy primer. It should be noted that the SERVOJET nozzle system was operated with a total pressure drop of 37.2 MPa (5,400 psi); however, due to the internal pressure drop at the Helmholtz chamber, the exit orifice pressure drop was about 32.7 MPa (4,750 psi). Thus, the jet velocity for the SERVOJET was about 256 m/s (840 ft/s), or slightly lower than the 265 m/s (870 ft/s) for the L&W nozzle operated at 35.2 MPa (5,100 psi). The total power absorbed by this SERVOJET system was about 34.7 kw (46.6 hp) versus about 32.4 kw (43.4 hp) for the L&W nozzle. Comparable results were obtained on the graphite reinforce epoxy panels, as typified by Figure 6.

Rock Cutting

A feasibility study[2], comparable to the paint removal program described above, was undertaken, with the objective of determining whether self-resonance could improve the rock cutting capability of low velocity water jets (Chahine, et al. (1982a)). Additional

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[1] Contract No. NOOO14-82-C-0143.

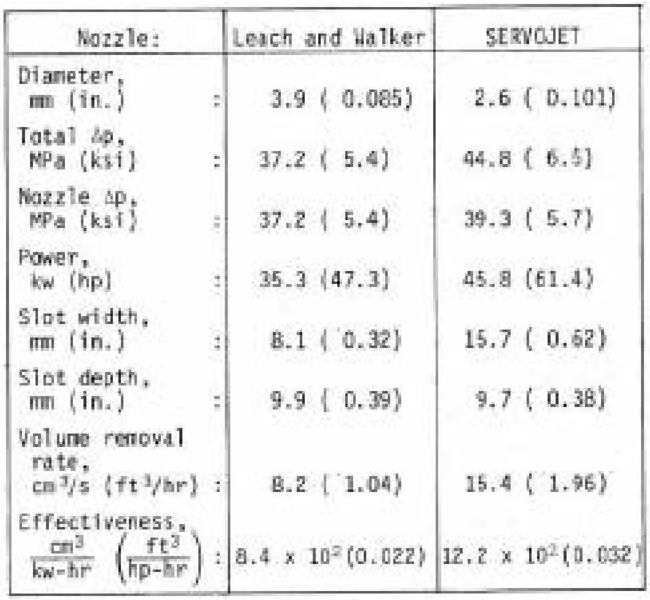
[2] NSF contract no CEE-8114063.

high velocity tests have been run recently, and results from each of these test series will be described.

The importance of the self-induced pressure fluctuation amplitude is demonstrated by the results summarized in Figure 7, for slot cutting trials on samples of Berea sandstone. In the upper portion of this figure it is seen that the optimum pressure fluctuation (of about 8 percent) inside the nozzle occurred at a jet velocity of 91 m/s (300 ft/s). The lower portion of Figure 7 shows that the maximum improvement of the SERVOJET nozzle, relative to the L&W nozzle, occurred at the velocity corresponding to maximum fluctuations in the self-resonating system. At the 91 m/s (300 ft/s) jet velocity, the STRATOJET nozzle removed about 33 cm^3/s (2 $in.^3/s$), absorbed a hydraulic power of 6.9 kw (9.3 hp), and hence the volume removal effectiveness was 17 x 103 cm^3/kw-hr (0.45 ft^3/hp-hr). The corresponding values for the L&W nozzle were: 3.3 cm^3/s (0.2 $in.^3/s$), 4.3 kw (5.8 hp), and 2.8 x 103 cm^3/kw-hr (0.07 ft^3/hp-hr). Therefore, the STRATOJET nozzle was over six times more effective, when operated at its optimum resonating condition.

The results of some higher pressure slot cutting tests on Indiana limestone are summarized in Table 1. Contrasted are the performance of an L&W nozzle, and a SERVOJET nozzle, each having smaller diameters than the nozzles used for the lower pressure tests on the sandstone.

Table 1. Slot cutting tests on Indiana Limestone
(standoff distance 28.7 cm (11.3 inches) Translation velocity 10.2 cm/sec (4 in/sec))



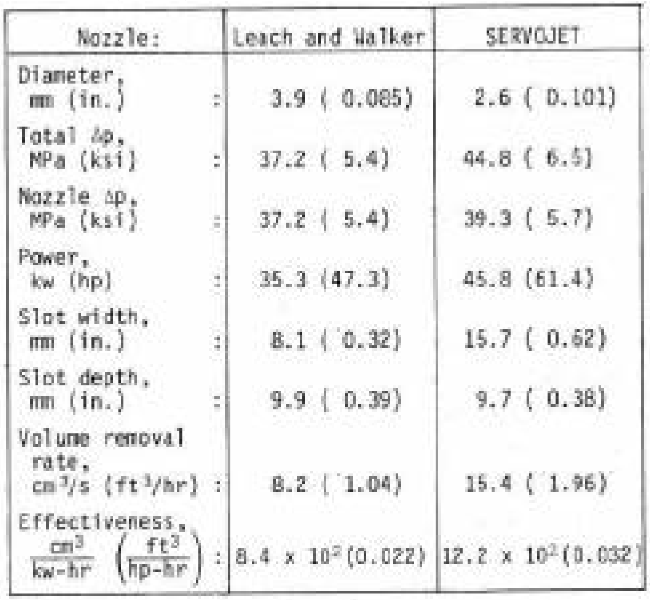
Nozzle:	Leach and Walker	SERVOJET
Diameter, mm (in.) :	3.9 (0.085)	2.6 (0.101)
Total Δp, MPa (ksi) :	37.2 (5.4)	44.8 (6.5)
Nozzle Δp, MPa (ksi) :	37.2 (5.4)	39.3 (5.7)
Power, kw (hp) :	35.3 (47.3)	45.8 (61.4)
Slot width, mm (in.) :	8.1 (0.32)	15.7 (0.62)
Slot depth, mm (in.) :	9.9 (0.39)	9.7 (0.38)
Volume removal rate, cm^3/s (ft^3/hr) :	8.2 (1.04)	15.4 (1.96)
Effectiveness, $\frac{cm^3}{kw\text{-}hr}$ $\left(\frac{ft^3}{hp\text{-}hr}\right)$:	8.4×10^2 (0.022)	12.2×10^2 (0.032)

It is seen that the main difference between the slots cut by these two nozzles lies in the slot width—almost twice as wide for the SERVOJET. The resulting effectiveness, despite the larger hydraulic power used, is almost fifty-percent greater for the resonating nozzle system.

Decontamination

Methods for rapidly removing toxic contaminants from military vehicles are now being sought by the U. S. Army. As part of an ongoing program[3] involving the development of equipment to evaluate water jets for this cleaning problem, a series of cleaning trials was conducted on painted panels containing deposits of a simulated contaminant. The importance of resonance is clearly indicated by the data shown in Table 2. Here, test results using the same exit nozzle orifice, with and without the use of the Helmholtz resonating chamber, are contrasted. As in the rock cutting tests discussed above, the self-resonance induced water slugs virtually doubled the path width cleaned.

Table 2. Cleaning of simulated contaminant
Exit Nozzle: oval, fan type 4.7 mm (0.185 in) equivalent diameter
Translation velocity: 61 cm/s (24 in/s)
Standoff distance: 30.5 cm (12 in)



Nozzle:	Leach and Walker	SERVOJET
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Nozzle Δp, MPa (ksi) :	37.2 (5.4)	39.3 (5.7)
Power, kw (hp) :	35.3 (47.3)	45.8 (61.4)
Slot width, mm (in.) :	8.1 (0.32)	15.7 (0.62)
Slot depth, mm (in.) :	9.9 (0.39)	9.7 (0.38)
Volume removal rate, cm^3/s (ft^3/hr) :	8.2 (1.04)	15.4 (1.96)
Effectiveness, $\frac{cm^3}{kw\text{-}hr}$ $\left(\frac{ft^3}{hp\text{-}hr}\right)$:	8.4×10^2 (0.022)	12.2×10^2 (0.032)

CONCLUSIONS

From the results achieved as of this time, in an ongoing effort to develop erosive water jets which have passive, internal pressure fluctuations, and hence deliver a series of water slugs, the following conclusions may be drawn:

1. A tuned, self-resonating nozzle system, consisting of a Helmholtz resonance chamber, followed by an organ-pipe segment, can be tuned to the intrinsic frequency of a water jet nozzle, for a wide range of jet velocities (nozzle pressure drops).
2. Pressure fluctuations inside the nozzle system correlate with target plate pressure fluctuations and optical measurements of the water slugs.
3. Self-resonating pulsed jets have produced substantially more effective cleaning and cutting results in comparison to comparable non-pulsed jets.

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[3] Under MRC Corporation Purchase Order No. 65390, a subcontract for ARRADCOM, CSL Contract No. DAAK1182-C-0150

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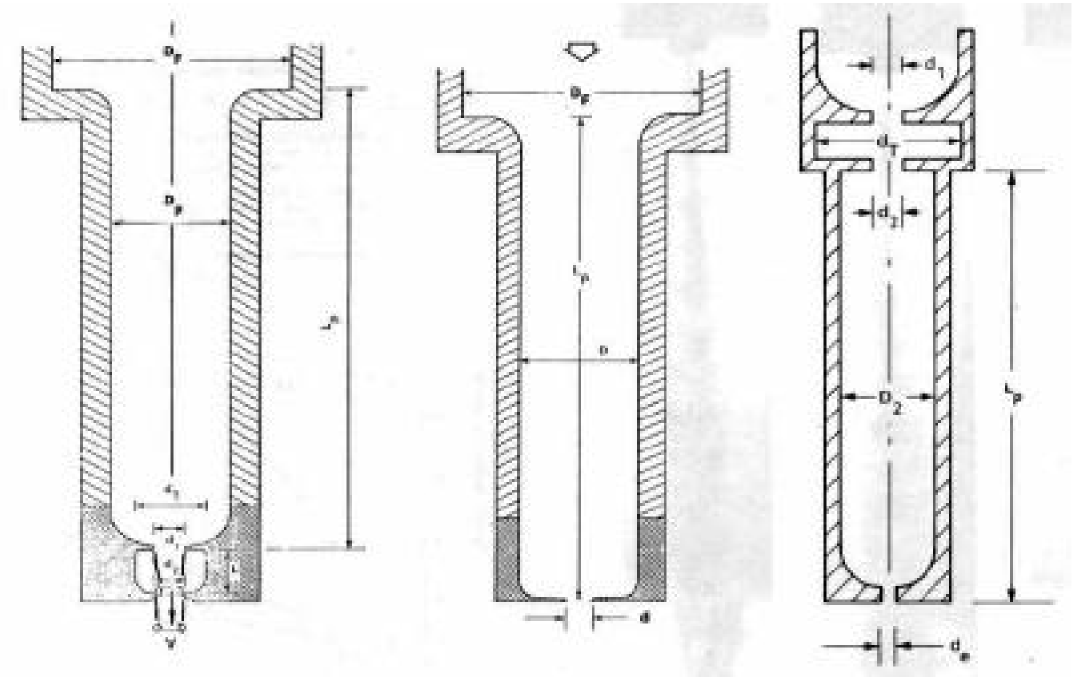


a. “PULSER” b.”ORGAN-PIPE” c.”PULSER-FED”

Figure 1. Self-resonating nozzle system concepts

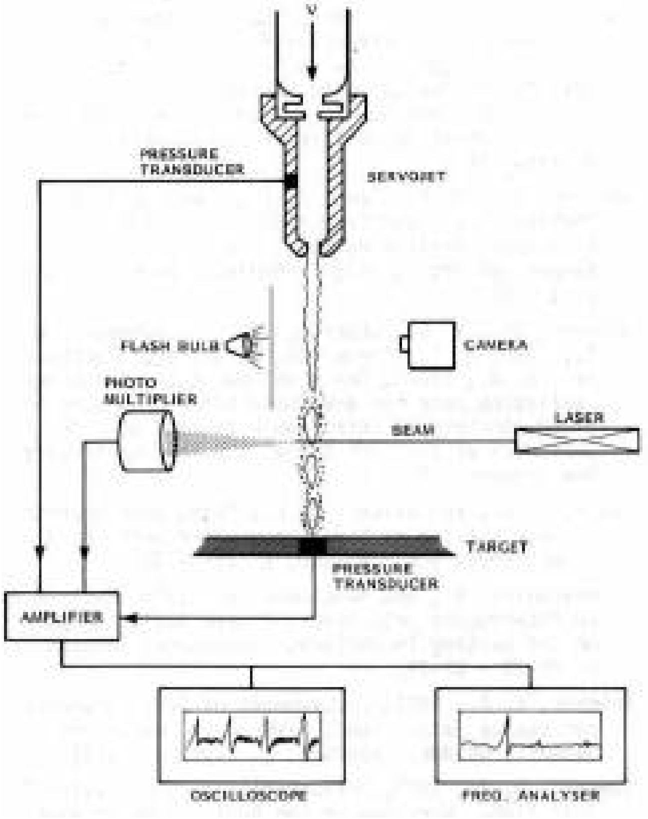


Figure 2. Experimental set-up.

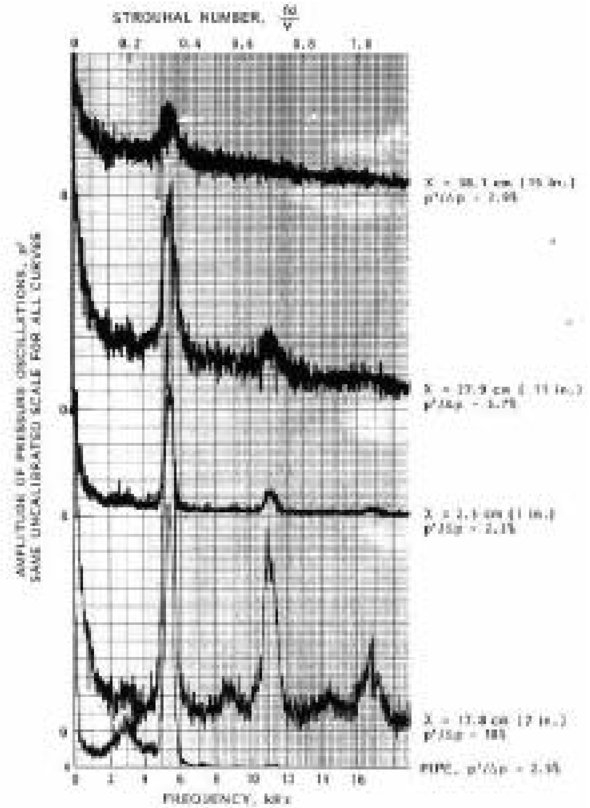
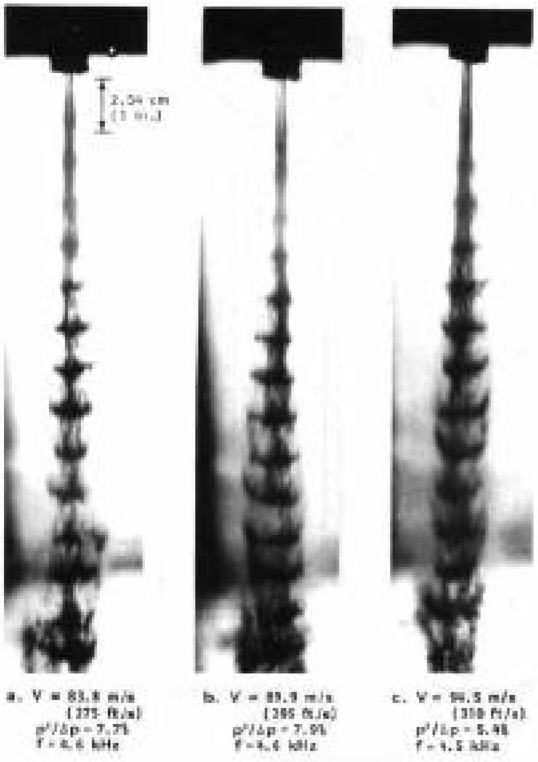


Figure 3. Pressure fluctuations in pipe and on target transducer at several standoff distances. V 65.5 m/s, (215 ft/s), d = 4.7 mm (0.185 in).



a. V = 83.8 m/s (275 ft/s) p'/Δp = 7.7% f = 4.6 kHz

b. V = 86.9 m/s (285 ft/s) p'/Δp = 7.9% f = 4.6 kHz

c. V = 94.5 m/s (310 ft/s) p'/Δp = 5.9% f = 4.5 kHz

Figure 4. SERVOJET appearance in the maximum oscillation region, d = 4.7mm(0.185 in).

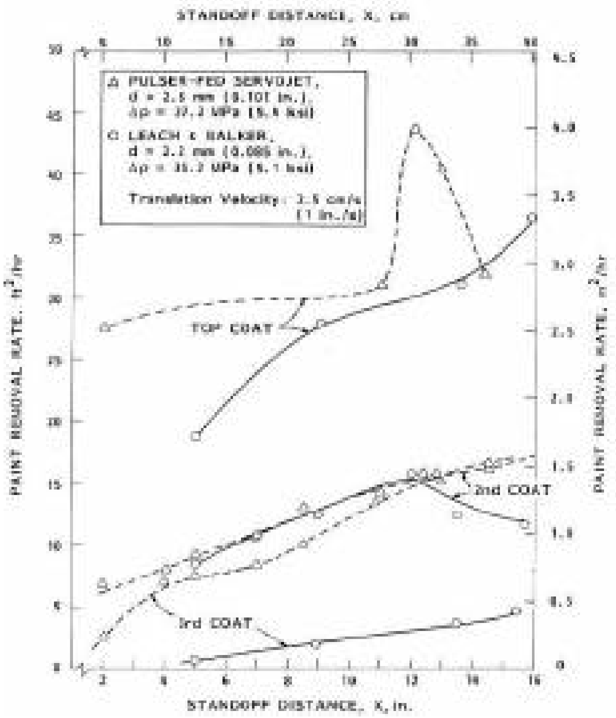
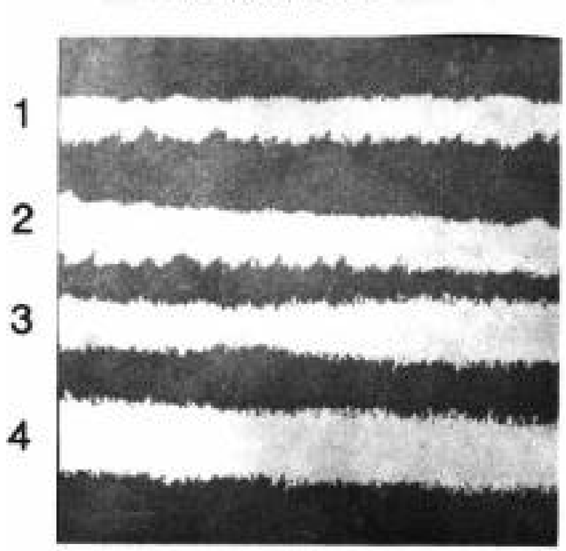


Figure 5 – Removal rate for various paint coatings on aluminum aircraft panel.



RUNS 1 & 2: LEACH & WALKER NOZZLE
d = 2.2 mm (0.085 in.)
Δp = 35.2MPa (5.1 ksi)

RUNS 3 & 4: SERVOJET NOZZLE
d = 2.6 mm (0.101 in.)
Δp = 37.2 MPa (5.4 ksi)

	One Pass		Two Passes	
Run:	1	3	2	4
Paint Removal Rate: m^2/hr (ft^2/hr)	1.16 (12.5)	1.45 (15.6)	0.72 (7.8)	0.95 (10.2)
Effectiveness: m^2/kw-hr (ft^2/hp-hr)	0.036 (0.29)	0.041 (0.33)	0.022 (0.18)	0.027 (0.22)

Figure 6. Comparative Paint removal trials, gray areas are polyurethane top coat, white areas are epoxy primer.

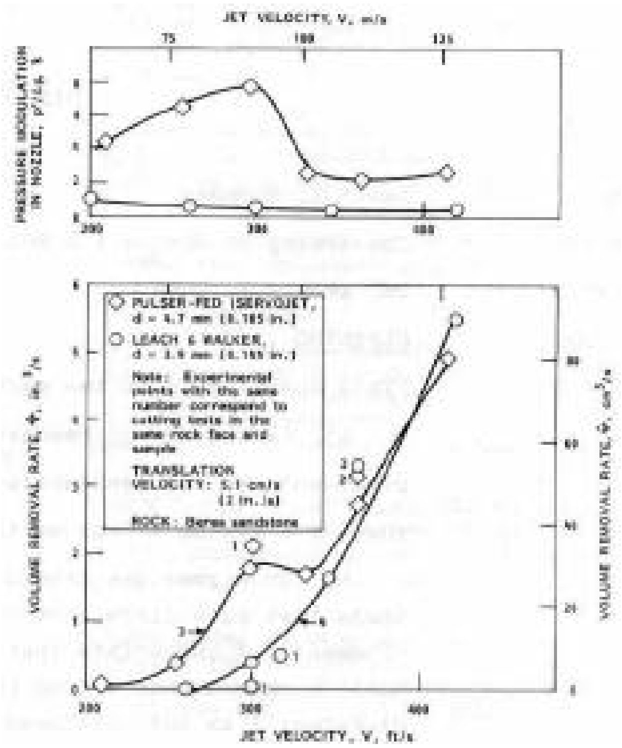


Figure 7. Pressure fluctuations in nozzle tube and rock cutting results for pulsed and non-pulsed nozzles.

DISCUSSION

NAME: David A. Summers
COMPANY: University of Missouri - Rolla

QUESTION: This question is in two parts:
a) Is the use of resonatingly pulsated jets limited in any way by pressure? We can use cavitation, for example, to lower the operating pressure of a system - can we do this with a pulsating system?"
b) At higher jet pressures, above the rock threshold pressure, is there that much difference between a Leach and Walker and a resonating jet? (Comment: I appreciate that you take good care to make a good resonating nozzle - given that a good Leach and Walker nozzle will cut 2,000 nozzle diameter; I am not convinced that you take as good care to test against comparable quality Leach and Walker designs.)

NAME: Bruce Williams
COMPANY: Liquid Lasers, Inc.

QUESTION: "At what pressures has the self-resonating pulsed jets been used?"

NAME: Mohamed Hashish
COMPANY: Flow Industries

QUESTION: "The concept of the 'servojet' is quite intriguing; however, for a valid comparison of its cleaning rates, or erosivity, with conventional steady water jets, the Leach and Walker nozzle is not the most effective cleaning tool. If you distribute the power used of 32 Kw approximately over many smaller steady jets, the cleaning effectiveness will exceed that of Leach and Walker nozzle, and probably that of the 'servojet'. I suggest you make this comparison with the best steady jet arrangement, also with the best "servojet" arrangement

ANSWER: Two of the questions (from Dr. Summers and Mr. Williams) ask about pressure usage with self-resonating pulsed jets. To date, this type of nozzle system has been operated over a range of from about 500 to 10,000 psi. Although we do not envision any intrinsic limitations to the phenomenon, the pump capacity in our laboratory has restrained us to the 10,000 psi value. In each case which we have examined the SERVOJET nozzle systems served to provide the same advantages previously seen for CAVIJET nozzles, namely, the ability to provide enhanced erosivity at the same nozzle pressure, or comparable results at a lowered value of nozzle pressure, relative to conventional, steady water jet systems.

Drs. Summers and Hashish question the differences in performance we have reported using as a base-line the so-called Leach and Walker nozzle for the non-resonating nozzle. All of our nozzles received the same degree of care in manufacturing--none, of course, of the "jeweler's quality" that Dr. Summers has achieved with electroplating techniques. At any pressure, if we have good resonance, the

SERVOJET nozzles were seen to out perform a comparable Leach and Walker nozzle. By comparable, we mean a nozzle delivering essentially the same flow and pressure. Comparisons of performance are then made by normalizing the cutting or cleaning results by the hydraulic power delivered through each nozzle. This is certainly a valid way to compare two nozzle systems; however, as Dr. Hashish has suggested, this does not claim to be the optimum case for either the resonating or the non-resonating system. Indeed, we too have found situations where a plurality of smaller nozzles will out perform one larger nozzle which delivers the same hydraulic power. We have found, however, that the opposite case can occur for some cleaning or cutting situations. Optimization should not be confused with one-to-one comparisons of two similarly sized, single-orifice nozzle systems, wherein the normalization described above will certainly tell you whether you've improved things or made them worsen

NAME: James Evers
COMPANY: Southern Illinois University - Carbondale

QUESTION: "Did stand-off distances increase in your cutting tests as they did in Gene Nebeker's results?"

ANSWER: Dr. Evers asks whether stand-off distances increase in our tests as they did for Gene Nebeker's tests. First, it should be emphasized that the optimum stand-off distance, X, for our self-resonating jets is a function of Strouhal number, Sd, and percentage of modulation: V/V, where V is the amplitude of jet velocity modulation and V is the mean jet velocity. Athough the main objective of our work to date has been to optimize jet erosivity and not to maximize the stand-off distance, by controlling these parameters, within a range we have yet to fully explore, we can vary X in accordance with the needs of a given cleaning or cutting application. In comparison to a comparable cavitating jet, we have found that a SERVOJET nozzle can be made to operate at greater stand-off distances. Also, if desired, we can reduce the stand-off distance by proper selection of Sd and V/V.