

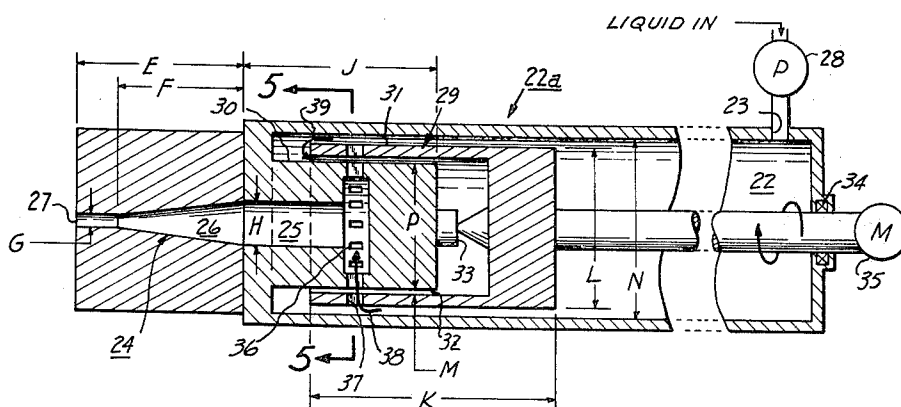
[54] **METHOD AND APPARATUS FOR PRODUCING AND UTILIZING PERCUSSIVE LIQUID JETS**[75] Inventors: **Eugene B. Nebeker**, Los Angeles;
Sergio E. Rodriguez, Woodland Hills, both of Calif.[73] Assignee: **Scientific Associates, Inc.**, Santa Monica, Calif.[22] Filed: **Oct. 29, 1974**[21] Appl. No.: **518,606**[52] U.S. Cl. **239/1; 239/101**[51] Int. Cl.²... **B05B 1/08; B05B 17/00; B44D 1/08**[58] Field of Search..... **239/1, 4, 101**[56] **References Cited****UNITED STATES PATENTS**

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[57] **ABSTRACT**

This invention relates to percussive liquid jets which consist of a sequence of liquid bunches, instead of a free stream of substantially uniform diameter. The percussive jets impinge on a target as a sequence of impulses rather than as a steady force, or as a cyclical sine-wave type force. The method for creating percussive jets from a continuous discharge of liquid consists of producing a relatively small cyclic variation of the discharge velocity, such that the resulting velocity variation along the free jet of liquid compels the jet stream to bunch at regular intervals. The invention includes apparatus for producing percussive liquid jets by said method. Percussive jets are applicable as controlled sources of liquid bunches, which may be separate drops, for cyclic impact or for where transformation of a jet discharge from a steady to a percussive impact is beneficial. One application of the method and apparatus for percussive jets is in the cutting or the excavation of rock and other materials.

5 Claims, 5 Drawing Figures

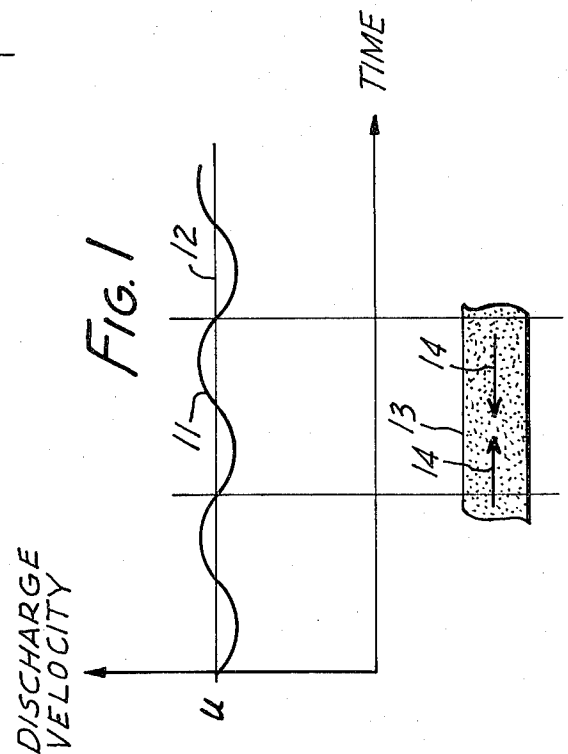
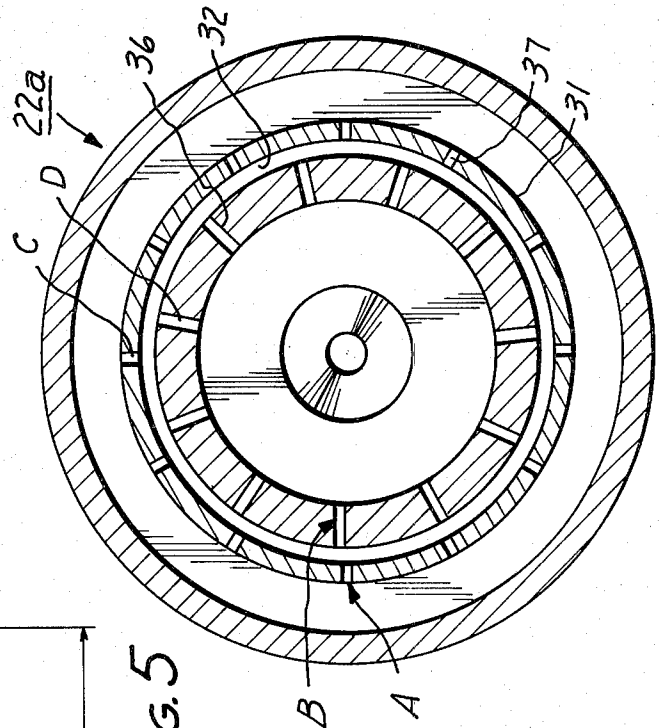
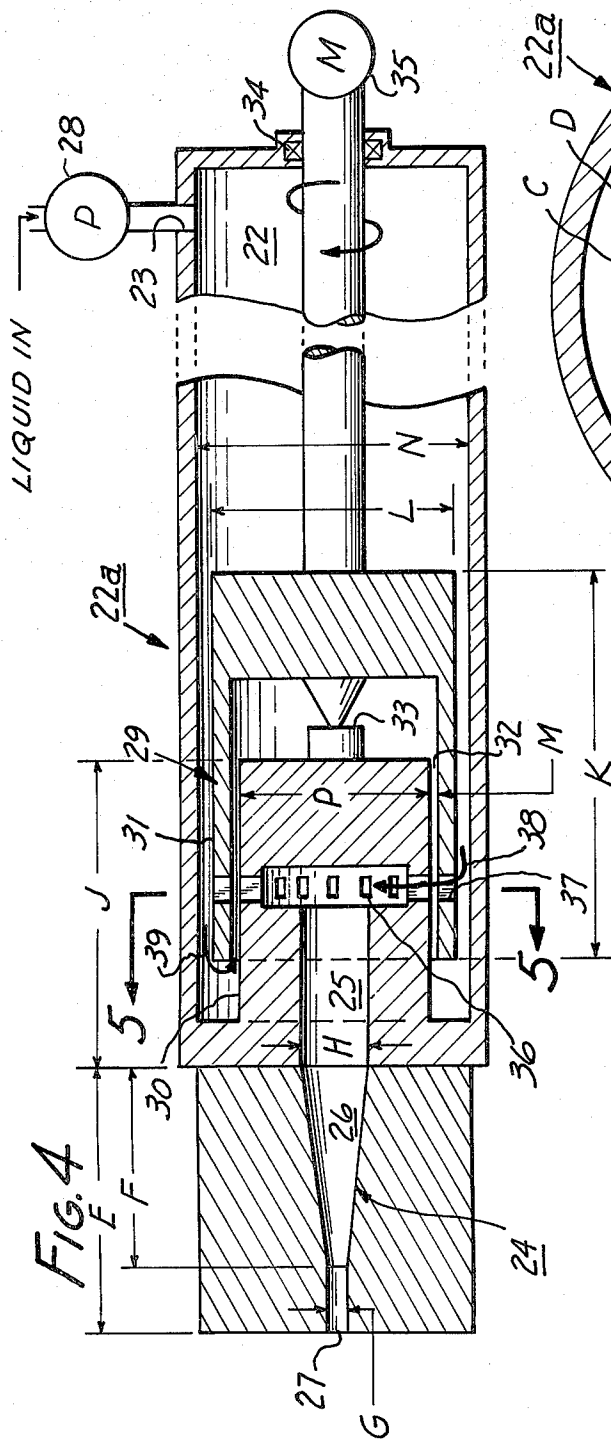
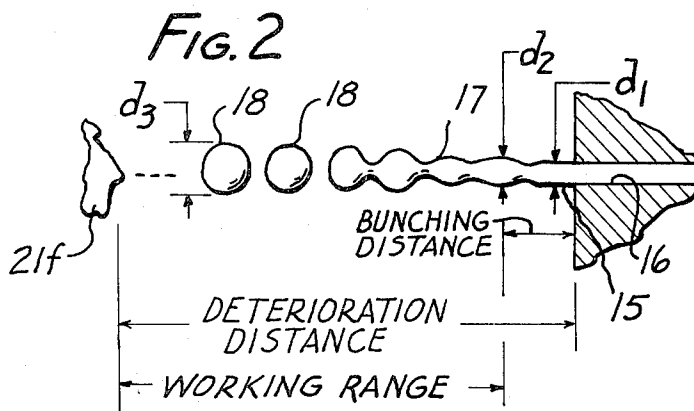
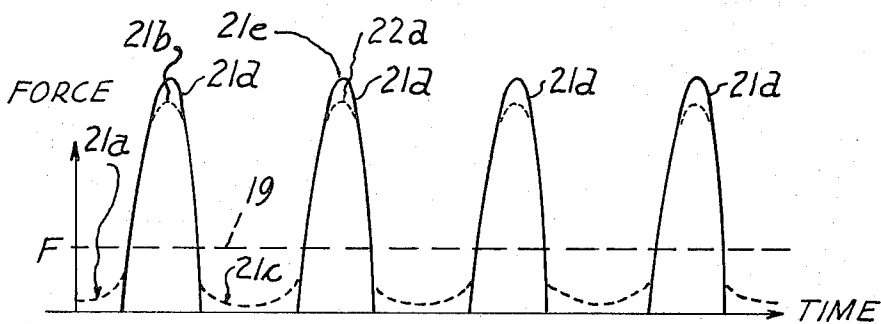
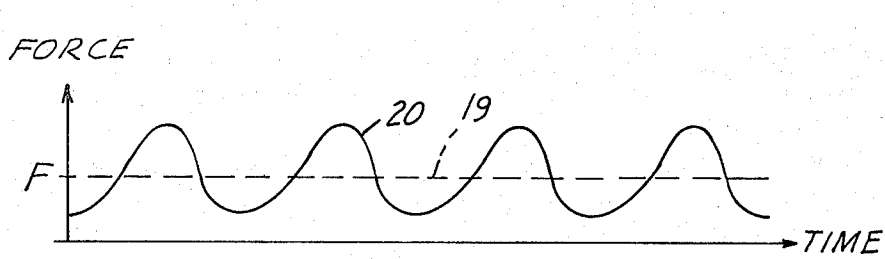


FIG. 3



METHOD AND APPARATUS FOR PRODUCING AND UTILIZING PERCUSSIVE LIQUID JETS

The percussive jet invention here described and its applicability to rock cutting were demonstrated under contract with the United States Army Mobility Equipment Research and Development Center. The method of the invention and the application were formulated earlier and were presented to said agency for its consideration.

The appellation "percussive jet" denotes a free stream or jet of liquid which, instead of remaining approximately uniform in diameter over its length, becomes a sequence of liquid bunches, either still joined by liquid or completely separated from one another. It is characterized by a variation in diameter, enlarging and reducing (reducing to zero when the bunches are separate from one another), the enlarged diameter being greater than the diameter of the stream where it issues from the nozzle. Percussive jet impact on a target exerts the momentum of the discharged liquid as a sequence of impulses, instead of as the essentially steady force which is applied by ordinary continuous jets, or instead of a sinewave type pressure variation. Regular and controlled sequences of liquid bunches and impulses are implied by percussive jets, not a random process.

For given operating conditions, percussive jet impact can have important advantages over ordinary jet impact, for example in rock cutting and excavation with water jets. Percussive jets can also find application as sources of repetitive impact, or as generators of streams of liquid drops.

An object of this invention is to provide a method for producing percussive jets.

Another object of this invention is to provide apparatus for producing percussive jets.

A further object of this invention is to provide a method and apparatus for producing percussive jets in rock cutting with water jets.

The method of the invention for producing percussive liquid jets consists in having the discharge velocity of a continuous, uninterrupted stream of liquid issuing from a nozzle increase and decrease cyclically by some amount small in relation to the average discharge velocity, whereby the free stream or jet will have alternate portions of slower and faster liquid along its direction of travel, whereby each faster portion of the jet will gradually overtake and combine with the immediately preceding slow portion, while gradually separating from the immediately following slower portion, thus producing alternate swelling and shrinking of the jet at regular intervals along its direction, and thus transforming the jet into a sequence of liquid bunches which become increasingly thick and pronounced with distance from the nozzle and can even ultimately become completely separated.

A preferred but optional method of obtaining jet discharge velocity variation consists in cyclically varying the liquid pressure at the inlet to the discharge nozzle. A further optional method consists of obtaining cyclic inlet pressure variation by means of a cyclically varying flow resistance in the flow path to the nozzle.

The apparatus of the invention comprises a flow chamber having an entry for pressurized liquid, a nozzle for discharging the liquid continuously as a jet, and means for cyclically varying flow resistance within the chamber, whereby cyclic variation is also produced in

the pressure upstream of the nozzle and in the jet discharge velocity, so that the jet stream becomes bunched and becomes a percussive jet. The means for varying flow resistance may conveniently be a modulator valve which cyclically changes effective through-flow area or length, and thereby the resistance offered to the passage of liquid.

A preferred but optional design for said modulator comprises a static and a rotary element, which elements may be coaxial parallel discs or nested cylinders, each element having flow openings which align varying with those of the other according to the relative angular position of the elements, whereby the effective flow channel through the modulator varies cyclically at least once per revolution of the rotary element. When the rotary element is steadily rotated, a regular cyclic variation in flow resistance is produced.

The method and apparatus for percussive jets may be utilized to produce a jet discharge of any velocity or pressure, any discharge cross-section shape and size, and any liquid or liquid solution. The percussive jet characteristics will be influenced to some extent by the aforesaid conditions and by the intrinsic properties of the liquid being discharged. Said influences may or may not be beneficial in a particular percussive jet process.

The method and apparatus of the invention may be applied with advantage, but not exclusively, in the excavation or cutting of rocks and other materials with water jets. High pressure water jets offer many operational advantages for excavation, but ordinary steady jets, or jets whose pressure fluctuates in a sine-wave manner, are neither sufficiently efficient in terms of the jet pressures required to attack hard rocks. Several considerations and actual tests indicate that percussive jets are more efficient than steady jets of comparable power and size, and that percussive jet impact provides superior capability for fracturing rock. The method and apparatus for percussive jets conveniently can be incorporated in equipment regularly used for excavation with ordinary water jets and can be utilized with entirely similar operating techniques. This adaptability follows from the fact that percussive jets are generated through a minor flow discharge perturbation, without affecting flow continuity and without requiring special pumps or special treatment of the water supply.

The above and other features of the invention will be fully understood from the following detailed description and the accompanying drawings, in which:

FIG. 1 is a graphic illustration of liquid discharge velocity as a function of time for a percussive jet;

FIG. 2 is an approximate showing of the formation of liquid bunches in a percussive jet after discharge from a nozzle;

FIG. 3 is a graphic illustration of the impact force produced by a percussive jet at different distances from a nozzle;

FIG. 4 is a side elevation, partly in axial cross-section, showing an embodiment of the invention; and

FIG. 5 is a cross-section taken at line 5—5 of FIG. 4.

The basic method and process of producing percussive jets are illustrated in FIGS. 1 and 2. FIG. 1 shows a qualitative plot of a cyclically varying discharge velocity against time, with line 11 corresponding to the instantaneous discharge velocity, whereas line 12 indicates the average velocity which is also denoted by the symbol u . The cyclic variation is typically small in comparison to the average velocity, so that the liquid discharge is continuous and uninterrupted at all times.

Schematic illustration 13 is a portion of the free jet of liquid corresponding to one discharge cycle in which the velocity is first slower, then faster, then the average. The resultant motion may be viewed as consisting of forward travel of the jet portion at the average velocity u , while the component liquid tends to flow towards the center of the portion, as indicated by arrows 14, in consequence of the velocity variation. Hence, as the jet portion goes forward, it also tends to shorten and swell in diameter, that is, it tends to "bunch." The process may be equivalently viewed as a case of the faster liquid within the cycle overtaking and combining with the slower. The process is necessarily accompanied by separation of each slow-fast jet portion from the preceding and succeeding ones. Thus, the cyclic variation in discharge velocity acts to transform the jet from a uniform stream to a sequence of bunches.

The instantaneous appearance of a bunching or percussive jet is shown diagrammatically in FIG. 2. The continuous liquid stream 15 is shown emerging from a nozzle 16 initially as an ordinary steady jet with an initial diameter d , at the nozzle orifice. The bunching process can begin only after the liquid leaves the nozzle. Bunching proceeds gradually, so that the liquid jet is increasingly bunched with distance from the nozzle (until the bunches achieve their maximum diameter). Diameter d_2 shows that beyond a "bunching distance," the diameter of spaced-apart portions substantially increases relative to the initial diameter d . Diameter d_3 is the diameter of a fully formed and separated bunch. The diameter of the stream necks down and finally becomes zero between the bunches. A region of the stream having a diameter d_2 or greater is defined as a "bunch."

FIG. 3 illustrates the nature of the impact produced by percussive jets upon striking a target. Two qualitative plots of impact force against time are shown and correspond with impact of a percussive jet with targets at different distances from the nozzle. Lines 19 and the symbol F denote the steady force which would be produced by an ordinary jet discharged at the average velocity of the percussive jet, which steady force is ideally invariant with distance from the nozzle. Line 20 shows a cyclic force variation corresponding to the instantaneous force exerted by the energizing stream within the bunching distance before it has travelled far enough to begin to bunch. The stream is not particularly effective for cutting or excavation. After travelling beyond the bunching distance, however, conditions become very different. Line 21a shows the force pattern "felt" by a target held beyond the bunching distance, where the bunches are still interconnected, such as where the diameter is d_2 . There will be a series of peaks 21b and valleys 21c, wherein the peaks are considerably higher above the average force level than the valley is below it. The target then feels a sequence of peaked impulses which are quite effective for cutting and excavating.

The preferred situation is shown by lines 21d, where the target is impacted by separated bunches of diameter d_3 . The peaks 21e are higher than peaks 22d, and the valleys are missing. All of the energy is represented beneath the arch-shaped line. It is evident that the maximum impulse will result from this type of impact. Because the bunching process of itself does not alter the momentum of the discharged liquid, the average force exerted by the percussive jet is ideally the same at any distance and corresponds to the steady force F of the equivalent ordinary jet.

The parameters which most directly affect the bunching flow process and formation of percussive jets are the amplitude, wave form, and frequency of the cyclic discharge velocity variation, the average velocity of the jet, and the jet size or diameter.

The amplitude of the velocity variation, or peak-to-peak change of line 11 in FIG. 1, determines the magnitude of the internal velocity components 14, which force the jet to bunch so that larger amplitude gives faster bunching and puts the jet transformation nearer to the nozzle. The wave form of the velocity variation, or shape of line 11 in FIG. 1, similarly affects bunching rate, because sharp or near squarewave cycling puts the fastest and slowest liquid in closer proximity within the jet. The frequency of the velocity variation, or its reciprocal the period, which is the time for one complete cycle of line 11 in FIG. 1, in combination with the jet velocity, establishes a wavelength, or length of jet stream involved in each individual bunching process. This wavelength determines the amount of liquid within each bunch and the time or distance required for development of significant percussive features. Jet diameter also determines the degree of percussive development, because the smaller the jet, the more significant the bunching deformation produced by a given discharge velocity variation.

The bunching process and percussive jet formation can also be affected by a number of secondary factors. Paramount among these are the dynamic effects of the air or other gaseous atmosphere into which the jet is being discharged. These aerodynamic effects grow rapidly in importance as the jet velocity increases, and are especially significant in very fast jets, such as used in excavation. Aerodynamic suction acts to enhance the growth of any deformations or protuberances on the surface of a jet. Aerodynamic drag reduces jet velocity and tends to disintegrate the jet stream. This drag effect is common to all free jets, which tend to lose a substantial portion of their discharge momentum after traveling distances on the order of 100 diameters from discharge, but could become especially pronounced in jets undergoing the percussive transformation as they present greater opportunity for air interaction with the liquid surface. A deteriorating bunch 21f is shown in FIG. 2, beyond a "deterioration distance," usually about 100 bunch diameters (d_3) from the nozzle orifice. The spacing between the bunching distance and the deterioration distance is sometimes called the "working range."

Among other factors which can affect the process, but presently are considered of lesser importance, are fluid friction, velocity profile produced by the discharge nozzle, and the intrinsic physical properties of the liquid. Fluid friction effects are probably of small significance because the flow is unconfined. An effect of discharge velocity profile is to create some transverse flow as the profile decays in the free jet, thus reinforcing bunching outflow produced by velocity variation. Liquid density, viscosity, and surface tension may significantly affect the coherence of the jet surface. Surface tension can have an important influence on jet surface deformation, but only in case of very short or sharp jet surface waviness. Surface tension instability is responsible for natural or spontaneous segmentation of free jets, but this phenomenon is not to be identified with the forced, controlled, bunching utilized for percussive jets.

Cyclic variation of the jet discharge velocity can be produced by the preferred method of cyclically varying the liquid pressure at the inlet of the discharge nozzle. Since the free jet discharges into a fixed ambient pressure, variations in nozzle inlet pressure produce variations in stream kinetic energy or velocity at the nozzle discharge. In utilizing this method, consideration must be given to the capability of the nozzle passage for responding to the impressed pressure variation. The longer this passage and/or the greater the cyclic frequency of the pressure variation, the smaller the velocity variation amplitude communicated to the discharge from a given inlet pressure variation.

Cyclic variation of the nozzle inlet pressure can be produced by cyclically varying the flow resistance upstream of the nozzle. Flow stoppage need not be produced, or even approached, but only a resistance variation consistent with the intended small variations in inlet pressure and discharge velocity need be provided. The method depends on having a liquid volume between the varying resistance and the nozzle, which is only a small fraction of the total volume upstream of the nozzle. With this condition, the resistance variation is primarily manifested as the desired variation in the nozzle inlet pressure. The overall process may be viewed as a variation in the total resistance between the upstream flow and the nozzle discharge, with a resulting variable discharge rate and velocity.

Varying flow resistance may be implemented by means of a modulator valve which cyclically changes its effective throughflow area and/or length, and hence its resistance to the passage of liquid. A modulator of this kind can conveniently operate by the movement of a set of flow openings on a rotary element past another set on a static element. These elements, which could be coaxial parallel discs or nested cylinders, would be installed so that the flow is induced to pass through both sets of openings. Since the effective flow passage and resistance will depend on the alignment of the two sets of flow openings, and since this alignment varies according to the relative angular position of the two elements, steady rotation of the rotary element will produce a cyclic variation in flow resistance. The number of resistance cycles per revolution of the rotary element will depend on the number of flow openings utilized. For example, if the static element has N and the rotary M openings, and if N and M have no common factors, then $(N \times M)$ cycles are obtained per revolution. The magnitude of the resistance change generated will depend in complex manner on design variables, including the area, shape, and disposition of the flow openings, plus the running clearance between the static and rotary elements.

FIGS. 4 and 5 illustrate an apparatus 22a for carrying out the method and objective of the invention. The apparatus includes a flow chamber 22 provided with a liquid entry 23 and a liquid discharge nozzle 24 having an inlet 25, a passage 26, and discharge opening 27. Entry 23 receives pressurized liquid from any convenient supply, such as pump 28. The nozzle passage 26 is shaped according to conventional designs for an efficient conversion of pressure to kinetic energy, with the reservation that this passage should not be so long as excessively to impede the production of a cyclic velocity variation at some desired frequency by a cyclic variation of liquid pressure at the nozzle inlet 25.

The flow chamber 22 contains a means 29 for producing a cyclic pressure variation at the nozzle inlet 25

which is a modulator valve consisting of a stationary inner cylindrical element 30 fixed to, or integral with, the nozzle 24 and a rotary outer cylindrical element 31 fitted coaxially over the inner element with a small clearance 32, so that the outer element is free to rotate supported against the flow by thrust bearing 33. The rotary element may be driven through an additional bearing seal 34 by an external motor 35, as shown, or it may alternatively be driven by a motor suitably mounted within the flow chamber 22. Said motors may be of any suitable type, such as electrical or fluid driven motors powered from separate sources, or fluid-driven motors or turbines driven by the pressurized liquid supply ultimately fed to the flow chamber.

A set of flow openings 36 is formed in the fixed element 30 and another set of flow openings 37 is formed in the rotary element 31. The two sets of openings are axially aligned, but their radial alignment depends on the angular position of the rotary element. The flow openings are significantly larger than the clearance 32, so that the flow goes preferentially through openings which are wholly or partly aligned. As can be seen from an examination of FIG. 5, when two openings, such as A and B, are nearly aligned, flow can readily occur radially through them, but when two openings, such as C and D, are angularly offset, throughflow is impeded by the smallness, length, and tortuosity of the intervening flow passage. In actual devices of this type, considerable flow can occur (see FIG. 4), even if not flow openings are well aligned, not only through both sets of openings, along a path indicated by flow line 38, but also by avoiding the upstream openings along another path as indicated by flow line 39.

The modulator valve 29 thus allows a continuous throughflow, but changes its effective throughflow area, length, and configuration significantly, according to the angular position of the rotary element, and therefore the resistance it presents to the flow. When the rotary element rotates steadily, a cyclical variation in flow resistance results and in turn produces a cyclical pressure variation at the nozzle inlet 25. In order to obtain a suitable pressure variation in this manner, the liquid volume between the modulator valve and the outlet; that is, the liquid volume within element 30, must be made small in relation to the liquid volume within the flow chamber 22 and the supply system 28.

The amplitude of the flow resistance variation produced by the modulator valve depends on the size, shape, and number of flow openings 36 and 37 in the static and rotary elements, on the clearance 32 between the elements, and on the cycling frequency. The frequency is determined by the speed of rotation of the rotary element and by the numbers of flow openings in the two sets. For example, if openings 36 number N and openings 37 number M , and N and M have no common factors, a total of $N \times M$ cycles will be produced for each revolution of the rotary element. Many design variations are possible as to the selection of sizes and number of openings.

In summary, the apparatus shown in FIG. 4 operates as follows. With a continuous flow of liquid through the chamber 22 and the nozzle 24, and with element 31 rotating steadily, the modulator 29 produces cyclic variation in flow resistance which in turn produces cyclic variation of liquid pressure at the nozzle inlet 25 and cyclic variation in discharge velocity at the nozzle discharge opening 27. According to the method of the invention, the cyclic variation in discharge velocity then

causes a bunching process in the discharged liquid jet which thereby becomes a percussive jet.

The method and apparatus for percussive water jets is especially applicable in rock excavation, or in the cutting of rock and other materials generally. High-pressure water jet impingement is an attractive technique for excavation owing to certain inherent operational advantages over other techniques. These advantages include continuity of operation, adaptability to various types and sizes of excavation, and safety from respiratory and explosion hazards. However, the applicability of water jets has been practically limited by their relatively high energy consumption for given excavation results. In addition, ordinary water jets lack effectiveness in cutting hard rocks like granite unless very high discharge pressures are used, but very high pressure discharges require special and unconventional equipment, with attendant expense, complexity, and discontinuity, so that practical gains have not been obtained in this manner.

Several theoretical considerations indicate that percussive jets would be more efficient and effective for removing rock than conventional jets of equal size and power. One important advantage is that percussive jets produce tensile stress in the target material by periodically relieving the impact force over all or part of the impact zone as each liquid bunch of the jet terminates its impact, which corresponds to the declining force portion of the force cycles shown in the lower graph of FIG. 3. This unloading is the necessary condition for obtaining absolute tension from stress waves reflected at the free boundaries of natural or fracturing cracks. Rock failure is very effectively induced by these tensile stresses, as brittle fracture occurs much more readily in tension than in compression.

Another important feature of percussive jet impact for cutting is the creation of very large compressive stresses of short duration on the arrival of each liquid bunch at the target. These stresses, which are not indicated in FIG. 3, occur on the rising force part of each impact cycle. They correspond to a waterhammer pressure rise as each liquid bunch first encounters the target. In addition, very high lateral velocities with corresponding shear and impact develop during the initial spreading of each bunch over the target as liquid is squeezed out between the leading surface of each bunch and the target.

Still another advantage can result from percussive jets applying energy in short-duration loads, rather than steadily. Shortening the load duration can reduce the energy required for removing unit volume, because the possibility of trapping energy in already-loose material is reduced.

While ordinary jets can have some discontinuous and initial impact effects on the target, owing to accidental discontinuities in the free stream, the percussive jet effects are much superior because the repetitive impulses are deliberate and the entire jet participates coherently.

Another significant aspect of the percussive jet impulse is that bunching enlarges the free stream's lateral cross-section from the initial dimensions of the nozzle discharge. Thus, both the impact area and the total force are increased, as shown by the force peaks in FIG. 3. A percussive jet can therefore achieve the surface coverage of a much larger conventional jet discharge, but, since the percussive impact is discontinuous, a much smaller water volume is being discharged.

This feature of percussive jets is important, because the presence of excess spent liquid at the target can adversely affect the impact of the oncoming stream.

Apparatus according to the invention has been used to produce percussive water jets for testing on rock. In one test, the average discharge velocity from the nozzle was about 1100 feet per second, and the jet discharge was cyclically varied by the apparatus at frequencies from 2,000 to 5,000 cycles per second. Sample rock targets were placed at distances of about 4 inches from the discharge. For comparison purposes, the same jet flow was discharged at the same rock targets, but without producing the percussive action; that is, as a conventional jet. The percussive jet cut limestone and sandstone with several times the energy efficiency of the conventional jet and produced cratering in a granite which could not be penetrated by the conventional jet.

As a final advantageous consideration, the application of percussive water jets would be relatively convenient and would not involve a loss of practicality in water jet cutting and excavation. This consideration derives from the fact that, according to the method of the invention, percussive jets are produced through a relatively minor flow perturbation at the point of discharge, and that, according to the apparatus of the invention, the means for obtaining the required flow perturbation are relatively simple and compact. Thus, percussive jet action could readily be incorporated into practical water jet excavation systems without requiring modification of the pumping and water distribution equipment or any other special treatment of the water supply. The percussive jets would also be applied through operating techniques entirely similar to those used with conventional jets.

The following is a set of suitable dimensions, in inches, for a device according to the invention:

E: 0.9 inch

F: 0.7 inch

G: 0.06 inch

H: 0.2 inch

J: 0.75 inch

K: 1.2 inch

L: 0.7 inch

M: 0.001 inch

N: 1.0 inch

P: 0.6 inch

Ports 36 and 37: 0.1 inch axially $\times$ 0.024 inch circumferentially

Number of static ports: 12

Number of rotating ports: 18

The device is operated with an inlet pressure of 8300 psig, and a rotary speed of 3,000 rpm. With 12 static and 18 rotary slits, 5,400 cycles per second are produced. A pressure drop of about 350 psig is produced by the device. The bunching distance was about 2 inches, the deterioration distance about 6 inches, and the optimum position of the surface to be cut was about 4 inches, all measured from the open end of the nozzle. These latter dimensions are measured axially, i.e., along the path of the jet.

The bunching distance and deterioration distance are parameters of a given set-up, and are subject to observation and adjustment.

It has been found that a frequency of at least 1000 cycles per second is necessary for practical excavation and cutting, and higher frequencies appear to improve the performance. Best performance is attained if the

average pressure of the stream exiting from the nozzle is at least 1000 psig.

This invention is not to be limited by the embodiments shown in the drawings and described in the description, which are given by way of example, and not of limitation, but only in accordance with the scope of the appended claims.

We claim:

1. A method for creating a percussive liquid jet from a continuous jet discharge consisting of producing a relatively small cyclic variation of the discharge velocity about its time average, whereby the free jet is given a lengthwise variation in forward velocity compelling the free jet to become a bunched stream with a change in lateral diameter occurring periodically along the length of the stream.

2. The method according to claim 1 in which said cyclic variation of the discharge velocity is obtained by producing a cyclic variation of the liquid pressure at the inlet to a discharge nozzle.

3. The method according to claim 2 in which said cyclic variation of the liquid pressure at the inlet to the discharge nozzle is obtained by producing a cyclic variation of flow resistance in the flow of liquid to the nozzle.

4. A method for cutting the surface of a body of material comprising impinging on said surface a modulated stream of water, said stream issuing from a nozzle as a coherent uninterrupted bunching stream having different internal axial velocities from point to point along its direction of axial flow, whereby beyond a bunching distance the lateral diameter of the stream varies periodically along the length of the stream without substantial deterioration until after the stream passes a deterioration distance, and maintaining the surface of the material to be cut between the said distances.

5. The method according to claim 4 in which bunches are formed at the rate of at least 1000 per second.

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