fluid amplifiers

FLUID AMPLIFIERS

JOSEPH M. KIRSHNER, *Editor*

Chief, Fluid Systems Branch
United States Army Materiel Command
Harry Diamond Laboratories, Washington, D.C.

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PREFACE

Although no-moving-parts fluid devices of one kind or another have been in existence for many years their use in control systems and logic circuits became realizable only after fluid amplifiers were invented.

The disclosure, in March, 1960 by the Diamond Ordnance Fuze Laboratories (now the Harry Diamond Laboratories), of the principles of the first fluid amplifiers not only launched a new technology known variously as fluerics, fluidics, fluid amplification, etc., but also sparked additional interest in internal aerodynamics, separated flows, and fluid circuit theory Interest has spread to many countries around the world; four conferences or symposia have already been held devoted solely to this subject, and special sessions have been set aside at several technical society meetings for its discussion.

Devices have been built and operated with nozzles as small as two thousandths of an inch and as large as five feet. Systems have been operated containing as many as one hundred or more no-moving part fluid components. A fourteen-bit counter approximately one-third of a cubic inch in volume has been demonstrated. Fluid devices have been successfully used as controls on jet engines, missiles, and railroad trains.

After the invention of the fluid amplifier, a team was assembled at the Diamond Ordnance Fuze Laboratories to investigate no-moving-parts devices and circuits and the associated physical phenomena. Since the members of this team were of assorted scientific disciplines, several DOFL staff members undertook to provide them with a common background by giving weekly lectures on fluid dynamics and circuit theory. The lectures were written out and copies disseminated. Eventually as the esearch progressed all the team members took turns in describing what they were doing and what was being done outside HDL. Nearly all of the material discussed was also written up in the form of internal reports.

Then in June of 1964 the material was revised and expanded and presented as a one week course at the Catholic University of America by lecturers from the Harry Diamond Laboratories. Subsequently the material was further revised and presented by me as a one-semester course at the Catholic University. Because of the interest shown in the subject throughout the world and the lack of a text on the subject, we felt that this material should be published, and the result is the present volume.

The primary purpose of this text is to point out and explain most of the relevant physical phenomena and to introduce some of the necessary techniques of this new field. So much significant material has recently been published that space limitations allow discussions of only a fraction of what has been done. We have therefore limited ourselves primarily to what we believe will be most useful for a good physical understanding of the basic concepts.

Throughout we have tried to relate the mathematics used to physical models. Efforts have been made to discuss complex mechanisms in a simplified and what we believe to be an original manner.

Although the author or authors listed are primarily responsible for the chapters listed, much has been contributed directly and indirectly by other members of the HDL staff; in particular we would like to acknowledge the work of John Burke, Carl Campagnuolo, Vondell Carter, Richard Deadwyler, Robert Dockery, Norman Eisenberg, Jonathan Fine, John Foxwell, Wilmer Gaylord, Allen Holmes, Joseph Iseman, James Joyce, Jr., George Mon, Gary Roffman, Leonard Sieracki, Henrik Straub, Kenji Toda, Richard Trapani, Harry White, Kenneth Woodward, and Edward Wright.

The entire text was read and discussed with Robert Hatcher who made many helpful suggestions and then again reread by Theodore Godfrey who also made many useful comments.

Special thanks are due to I. Rotkin for originally suggesting the writing of such a text and to Dr. M. Apstein and Lt. Col. M. S. Hochmuth for their continual help and encouragement.

Joseph M. Kirshner

FOREWORD

For most of recorded history, the bulk of the energy which man has controlled has been that which he processes with his body. At 2,500 calories per day, this turns out to be about 3 kilowatt hours, or about 4 horsepower hours per day, and most of this is used to keep him warm. Man has always been able to think of more things to do than he has had the energy to do, so it isn't too surprising that he looked for means of controlling energy beyond that in the food ingested.

One of the early ways of controlling additional energy came about through the domestication of animals. A man with a horse can raise his "energy" standard of living by an order of magnitude, even assuming the horse works only a 40-hour week. Wild animals expend large amounts of energy, but they do not contribute to man's energy standard of living because the element of *control* is missing.

The direction of energy is what man wants and what he needs in order to achieve many of his goals, and he has been a prolific inventor of means to do this: water wheels, gunpowder, steam engines, gasoline and diesel engines, jet engines, nuclear fission, and nuclear fusion are means of bringing various sources of energy under his control.

Now it is obviously desirable that the *controlled* energy ought to be greater than the energy expended in the controlling process, or, to be a little more exact, the result accomplished by the *controlled* energy should be greater than the results which could be accomplished by the *controlling* energy acting directly. If this condition is met, then the process has amplification. There are, of course, many necessary and useful controls which do not have amplification, but those with amplification have received much more attention.

Hydraulic, pneumatic, steam, and electrical controls are examples of amplifying devices, some giving a continuous range and some giving only discrete levels of output power. Today we would class them as either "analog" or "digital" systems. Up until about a half century ago, the operation of all these systems required the motion of mechanical parts to accomplish their purposes. Then the vacuum tube came in, and for half a century has dominated the high-speed electrical control of energy without the use of any moving mechanical parts. In the vacuum tube, the same medium is used at input and output, that is, electron flow controls electron flow. This is a very happy state of affairs for elements intended for connecting together into complex systems. Similarly, the exciter generator in a power generating station delivers a large excitation current to the alternator with high efficiency, and in this capacity, it is acting as an electrical amplifier. This kind of electrical amplifier is, however, neither sensitive enough nor fast enough to handle very small radio signals (often less than a billionth of a watt).

The transistor has augmented the capabilities of, and in many cases replaced, the vacuum tube, and has retained two important characteristics: no moving parts and single-medium control.

Let's see what has been happening to fluid systems for the past few hundred years. The control valve or gate in a water wheel control system is an elegant and high-gain fluid controller. The sliding valve on a steam locomotive and the regulating valve on a steam turbine are effective controllers of large powers. The capabilities of these controls and many others are such that if electrical systems had not been developed around the turn of the century, there is little doubt that fluid distributing systems would have taken over a considerable burden In London, Manchester, and Glasgow, hydraulic power transmission systems were installed with line pressures from 700 to 1,600 pounds per square inch. The fluid was water. Cast iron pipe six inches in diameter permitted delivery of 140 horsepower over a 10-mile stretch with 10 percent line loss. While such systems were expensive to install and maintain, they did operate. Some work was also done on wave transmission hydraulic systems (i.e., alternating flow systems); some of them were even three-phase systems.

During this same period, pneumatic systems were being exploited, mostly in France. In the 17th Century, Denis Papin compressed air with power from a water wheel and transmitted it through tubes to be used elsewhere. From 1800 to 1900, many improvements in compression, distribution and use of air were made as the thermodynamics involved became better understood. Pneumatic systems became popular in mines for safety reasons. The ready availability of air made pneumatics popular for uses ranging from rock drills and pneumatic wrenches to railroad brake systems. All of these (amplifying) fluid systems required moving parts to control the air flow.

There was one man who sought to operate a pneumatic system without moving parts. To quote from the 1947 issue of the *Britannica*:

> A remarkable pneumatic transmission system (Fig. 1) was installed in 1890 by Priestly in Snake River desert, Idaho. On the north side of the river is a cliff, nearly perpendicular, about 300 ft high. One hundred and ninety feet above the river, for a considerable distance along the cliff, streams of water gush out from between the bottom of the great

lava bed and the hardened clay of the old lake bottom. Priestly, . . . , built a pipe line down the bluff and trained the water into it in such a way that it carried a very considerable quantity of air in the form of bubbles along with it down the pipe, compressing it on the way. The air was collected at the bottom in a covered reservoir, and taken up the cliff again to the lower part of an inverted siphon pipe, one side of which reached down from the water-supply about 60 ft and the other side reached up and over the bluff. Allowing the water to fill both sides of the pipe of the level of the water-supply, he admitted his compressed air at about 75 lb pressure into the long side of the pipe near the bottom, and soon had water flowing upwards over the cliff and irrigating a large tract of rich lava land. He had made a power, a transmission and a motor plant without a moving part. A similar compressor was installed near Montreal, Canada, in 1896; another at Ainsworth, British Columbia, in 1898; and another at Norwich, Conn., in 1902. These are called hydraulic air compressors and show an efficiency of about 70%. They are particularly adapted to positions with a large flow of water with a slight fall or head.

This interesting development is not described in some later editions of the

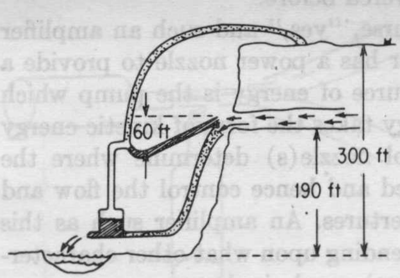

FIG. 1. Water lift, using no moving parts.

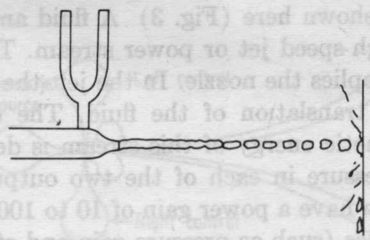

FIG. 2. Breakup of jet by sound.

Britannica presumably being displaced by more modern technological developments.

Meanwhile, back in the physics laboratory, Edison in the United States, and C. V. Boys in England, performed some very interesting experiments in which they achieved sound amplification by vibrating an extremely fine jet of water, then allowing the jet to fall on a sounding board (Fig. 2). The surface tension forces provide a source of energy, and the jet breaks up into droplets whose size is determined by the sound. The sound does not have "full control," being able only slightly to retard or speed up the stream break-up process. This subdivision into droplets then controls the timing of the delivery to the diaphragm of the kinetic energy of the stream.

The various ways of controlling energy referred to so far are, except for the transistor, more than a half century old. The tools available for discussing and analyzing them today are, however, rapidly improving. For example, the concepts of impedance, gain, available power, and the whole field of network theory permit analysis of *linear* systems. More recently, our understanding of system stability, distributed systems, and parametric changes, and above all our tendency to look at all systems from an information transfer or "black box" viewpoint—all of these have warranted taking another look at many old systems. In the particular field of fluids, rapid advances in aerodynamics and hydrodynamics, spurred on by the needs of airplanes, torpedoes, rockets, turbines and jets, have provided a much improved understanding of fluid flow in recent years, though the basic properties of fluids, nonlinearities in particular, assure that analysis of fluid systems will always be more complex than the analysis of similar electrical systems.

Today a fresh view is being taken of fluid-actuated systems, triggered by a question I had the good fortune to ask and answer. That question was: Is it possible to make an amplifier (one with a power gain) for use in a fluid-actuated system without the use of any moving parts? Not a very impressive sounding question. For some reason it doesn't seem to have been asked before, or, if asked, not answered before.

The answer to our question is, of course, "yes," and such an amplifier is shown here (Fig. 3) A fluid amplifier has a power nozzle to provide a high-speed jet or power stream. The source of energy is the pump which supplies the nozzle. In the jet the energy takes the form of kinetic energy of translation of the fluid. The control nozzle(s) determine where the kinetic energy of this stream is delivered and hence control the flow and pressure in each of the two output apertures. An amplifier such as this can have a power gain of 10 to 100, depending upon what other characteristics (such as pressure gain and efficiency) are desired.

Interacting fluid streams were used in 1946 patents of jet relays by Braithwaite and Todd. Both of these permitted relative position determination, readout, and control, but neither used the deflected stream and neither was designed to conserve stream energy nor to achieve a power gain.

Hall in 1953, Harris in 1955, and Magnuson in 1959 were granted patents showing jets deflecting jets for sound generation, feedback signal interruption and bottle filling, but again none uses the energy of the deflected stream none is designed for good power gain, and none discusses gain or amplification.

Now taking a closer look at fluid amplifiers, we see that it is sensible to connect them in push-pull (Fig. 4), since each is a "beam deflecting" device rather than a "beam stopping" device, as is a triode. But connecting fluid amplifiers is just about the biggest problem in this field. There are good reasons for the difficulties: First, the basic forces in fluids in motion, as shown by the Navier-Stokes differential equations, are nonlinear (the inertial forces depend upon velocity squared and the viscous or frictional forces depend upon velocity), second, the continuity equation must hold (what goes in must come out)

Now there's nothing new or exciting about either of these, but they do have special significance in fluid amplification systems. With moving parts, it is easy enough to shut off fluid flow. Without moving parts, the continuing flow must be accommodated and properly discarded after its energy has been extracted. The fluid nonlinearity makes it a ready converter of its steady (or d-c) flow energy into fluctuating forms, resulting in the familiar noises and whistles of fluid jets, a consequence of the surface forces on the stream of fluid which conveys the signal. Electrical systems have their noises and parasitic oscillations too, but these are under fairly good control, due in part to the fact that the charges are influenced by "body" forces.

In spite of these characteristics and the resulting difficulties, the engineers and scientists working in this new field have developed many useful components, devices, and systems. Applications of fluid amplification

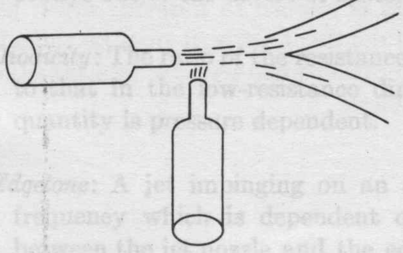

FIG. 3. Deflection of one stream by another.

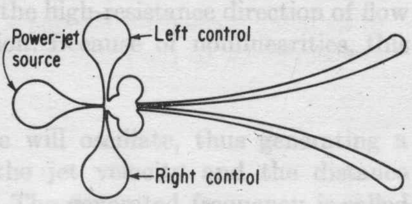

FIG. 4. Proportional fluid amplifier.

currently being investigated include: a heart pump, a respirator, and other medical devices, logic and timing circuits, rocket thrust vectoring, missile attitude control, automatic piloting of aircraft, hydrofoil control and jet engine control, and some industrial inspection and control. It is a little early to say just how far this new medium will go in each of these fields, but the inherent advantages of simplicity and ruggedness give strong impetus to the work. The term "simplicity" above does not necessarily refer to the state of understanding necessary to cause an all-fluid system to work properly. In fact, each device having significantly different characteristics usually points out the need for additional fundamental knowledge of fluid flow. The resulting practical impetus to research activity is aided by the realization that all-fluid systems can "think" in the manner of electronic systems (though not nearly as fast), that they can also deliver considerable amounts of power, and that full exploitation of this dual capacity requires better analysis and synthesis of fluid flow phenomena.

The rate of development of fluid amplification will depend heavily upon the increase in fundamental knowledge, as well as upon inventiveness and ingenuity. Its ultimate role in the control and computation field will not be known for years.

It is believed that the rate of progress toward understanding of these simple-looking devices will be considerably aided by this publication prepared under Mr. Kirshner's guidance by members of the Harry Diamond Laboratories, where fluid amplification started.

BILLY M. HORTON, *Technical Director*
Harry Diamond Laboratories,
Washington, D. C.

GLOSSARY

Certain terms used in this text are defined in this section; other definitions may be found by referring to the index.

Aspect ratio: The ratio between the depth of the channels of a fluid device and the width of the power jet nozzle.

Bleed, dump, and vent: A bleed or vent is an opening or passage between a fluid device and a reservoir and is therefore roughly equivalent to a ground junction in electronic circuits. A bleed in which steady flow is always out of the device or system is often called a *dump*.

Diodicity: The ratio of the resistance in the high-resistance direction of flow to that in the low-resistance direction. Because of nonlinearities, this quantity is pressure dependent.

Edgetone: A jet impinging on an edge will oscillate, thus generating a frequency which is dependent on the jet velocity and the distance between the jet nozzle and the edge. The generated frequency is called an edgetone.

Ideal gas: A gas whose molecules occupy zero volume and have no attraction for each other. The term is sometimes applied to mean a monatomic ideal gas.

Nozzle width: This designation is often used to mean the power jet nozzle width. Fluid device dimensions are usually normalized with respect to the power jet nozzle width.

Offset or setback: The amount by which each wall of the sudden enlargement just past the nozzle of a fluid device is set back from the nozzle. (D of Fig. 9.3)

Pressure recovery: The ratio of the total pressure above ambient recovered in the output of a fluid device to the total pressure above ambient in the power jet. Usually given as a percentage.

Primary and secondary flow These terms are used in two senses: (1) The fluid surrounding the jet of interest (the primary flow) is called the secondary flow when it has a velocity of its own (not due to interaction with the primary flow); (2) In a pipe bend the forces set up by the turning of the main or primary flow cause circulating flow patterns to be established which are also called secondary flow.

Spread factor: The coefficient in Goertler's expression for the velocity profile of a free jet which indicates the rate at which the jet spreads as it moves downstream.

Turndown ratio: The ratio of the output flow from a vortex triode with no control input to its output when the control flow is such as to give minimum output.

Two-dimensional fluid device: This term is applied to a device which has the same cross section at all channel depths; that is, it may be thought of as being formed by moving a two-dimensional pattern in a direction perpendicular to the plane of the pattern.

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