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# Determination of Fundamental frequency of a Fluidic Valve

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## ABSTRACT

This disclosure describes determination of a fundamental cutoff frequency of a fluidic valve that is independent of the fluidic cutoff frequency. A fluidic test apparatus is set up connecting a fluidic reservoir to one or more fluidic valve(s) and an adjustable load. The valve(s) are switched on and off at a specified actuation frequency. The actuation frequency is adjusted, and measurements are made over a range of different frequencies, e.g., about 0.1 Hz to about 500 Hz. Pressure gain as a function of frequency is determined over different fluidic loads and input pressures and is then utilized in conjunction with fluidic RC models described herein to determine an effective valve cutoff frequency that is independent of the different loads applied on the fluidic valve.

## KEYWORDS

- Fluidic control
- Fluidic valve
- Fluidic RC frequency
- Valve frequency
- Cutoff frequency
- Valve characterization
- Vibrotactile device
- Haptics

## BACKGROUND

Fluidic control systems and fluidic devices utilize fluids in motion and under pressure to perform a variety of functions such as sensing, logic, and control without the need for moving parts. A wide range of fluidic devices such as amplifiers, oscillators, sensors, active logic elements, transformers, transducers, etc. are available. Fluidic devices can provide high reliability under adverse operating conditions such as high temperature, intense radiation, etc. and are utilized in many commercial and industrial applications.

Most fluidic systems and devices utilize fluidic valves for flow switching. Fluidic valves direct fluid flow into a desired direction by utilizing the inertia of a fluid jet, which is usually accelerated in a nozzle. Flow control is achieved by deflecting the fluid jet, usually by another, small control flow issuing from a perpendicular control nozzle.

In the case of relatively low density fluids such as air, fluidic inductance (which in turn depends on inertia of the fluid) plays a relatively small role. However, for denser fluids, inertial effects (e.g., water hammer effects, etc.) can affect system dynamics, and fluidic inductance can play a more important role.

The fluidic response time of fluidic valves depends strongly on the resistive and capacitive loads (viscous damping and compressive effects, respectively) applied to the valve. Direct fluidic characterization of valve performance that is independent of the applied load is a challenge.

In one approach, valve performance and speed are measured visually and/or by utilizing optical/vibrational sensors. While this approach can be effective to characterize a valve under no-load conditions. However, valve performance under actual load conditions can be different. Besides, this approach doesn't take into account fluidic non-linearities that arise during positions in the valve cycle when it is partially open. Therefore, the true maximum frequency may be different from the effective cutoff frequency.

In another approach, valve performance is measured and specified over a set of frequencies and loads. However, this approach does not take into account native resistive and capacitive loads of the valve itself.

## DESCRIPTION

This disclosure describes techniques for characterization of high-frequency dynamics of fluidic valves. Per techniques of this disclosure, a series of controlled measurements are obtained over a range of operating conditions. The measurements enable determination of a fundamental cutoff frequency of the valve that is independent of the fluidic cutoff frequency.

In a fluidic valve system, there are generally at least two cutoff frequencies in operation that control the dynamics of the fluidic valve. A fluidic RC (Resistive-Capacitive) frequency of a valve is the frequency at which a given connected load (container) is unable to fully fill. Capacitive effects arise from a storage capacity of the container, while resistive effects arise due to restrictions to fluid flow. For an incompressible fluid, resistive effects are based on the elastic behavior of the container boundary. For a compressible fluid, resistive effects arise from the elastic behavior of the container boundary and from the self-compressibility of the fluid itself.

Fundamental valve frequency of a fluidic valve refers to a frequency at which the valve is unable to fully complete a cycle of valve opening and closing (shutting). When operated at its fundamental valve frequency, a fluidic valve is non-operational and does not allow fluid flow, even though visual and/or acoustic measurements may indicate that the valve is opening and closing.

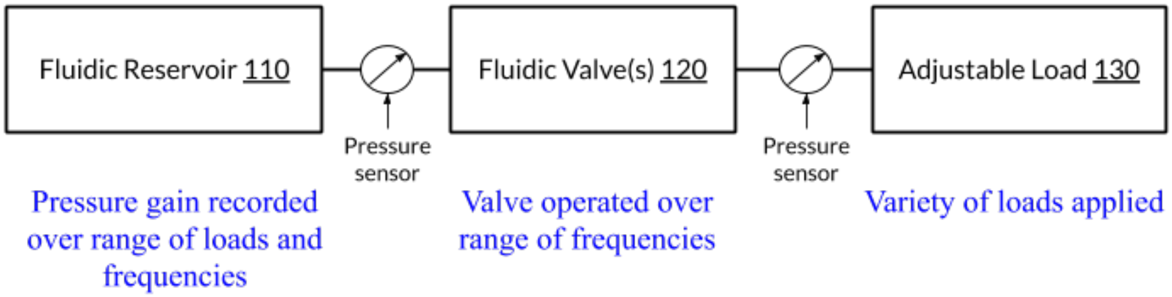


**Fig. 1: Measurement of the fundamental frequency of a fluidic control valve**

Fig. 1 illustrates an example set up for the measurement of the fundamental frequency of a fluidic control valve. Per techniques of this disclosure, the fundamental frequency of the fluidic control valve is measured by decoupling the load effects on dynamic fluid flow from the effects of the valve itself. Varying loads and input pressures are applied to the fluidic valve, and at each set point of load and input pressure, output pressure measurements are made as the fluidic valve is operated over a range of frequencies.

A fluidic test apparatus is set up connecting a fluidic reservoir (110) to one or more fluidic valve(s) (120) and an adjustable load (130). The valve(s) are switched on and off at a specified actuation frequency. The switching on and off of the fluidic valve causes the fluidic reservoir to oscillate between conditions of high pressure and low pressure. The pressure at the fluidic reservoir is recorded along with the input pressure. The actuation frequency is adjusted in suitable increments and measurements are made over a range of different frequencies, e.g., about 0.1 Hz to about 500 Hz. Above a certain actuation frequency of the fluidic valve, the fluidic reservoir is unable to attain the pressure applied at the input.

A pressure gain of the fluidic valve, defined as ***output pressure at reservoir / input pressure*** is determined at each applied valve frequency over a range of frequencies.

Based on the measurements, the pressure gain as a function of frequency is determined over different fluidic loads and input pressures, and is then utilized to determine an effective valve cutoff frequency that is independent of the different applied loads on the fluidic valve.

Various system models may be utilized in conjunction with the measurements to determine the valve cutoff frequency.

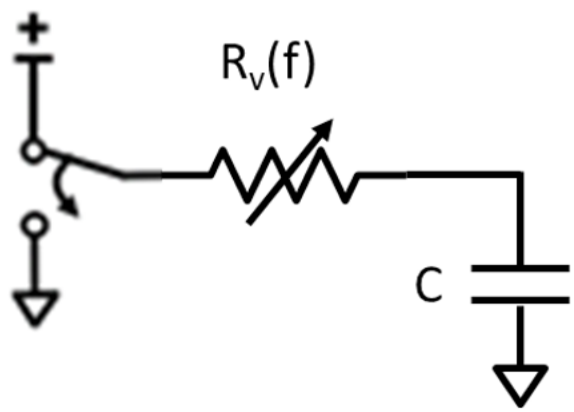


**Fig. 2: Fluidic RC model with Frequency-dependent Orifice Resistance**

Fig. 2 depicts an example fluidic RC model that includes a frequency dependent orifice resistance. The model assumes that the orifice area of the valve follows a first order dynamics based on a valve actuation frequency, and that the orifice area remains constant at a given operating frequency.

The valve orifice area frequency response is modeled by the equation:

$$|A(f)| = \frac{AO}{\sqrt{1 + \left(\frac{f}{f_1}\right)^2}},$$

and the frequency dependent orifice resistance by the equation:

$$R(f) = \frac{3.88e^8}{\frac{4A(f)}{\pi}}$$

The approximate system frequency response model is:

$$|G(f)| = \frac{1}{1 + \left(\frac{f}{\frac{k_0}{RC}}\right)^2 \left(1 + \frac{f}{f_1}\right)}$$

where the Fluidic RC cut-off frequency $f_0 = \frac{k_0}{RC}$ and $f_1$ is the valve cut-off frequency.

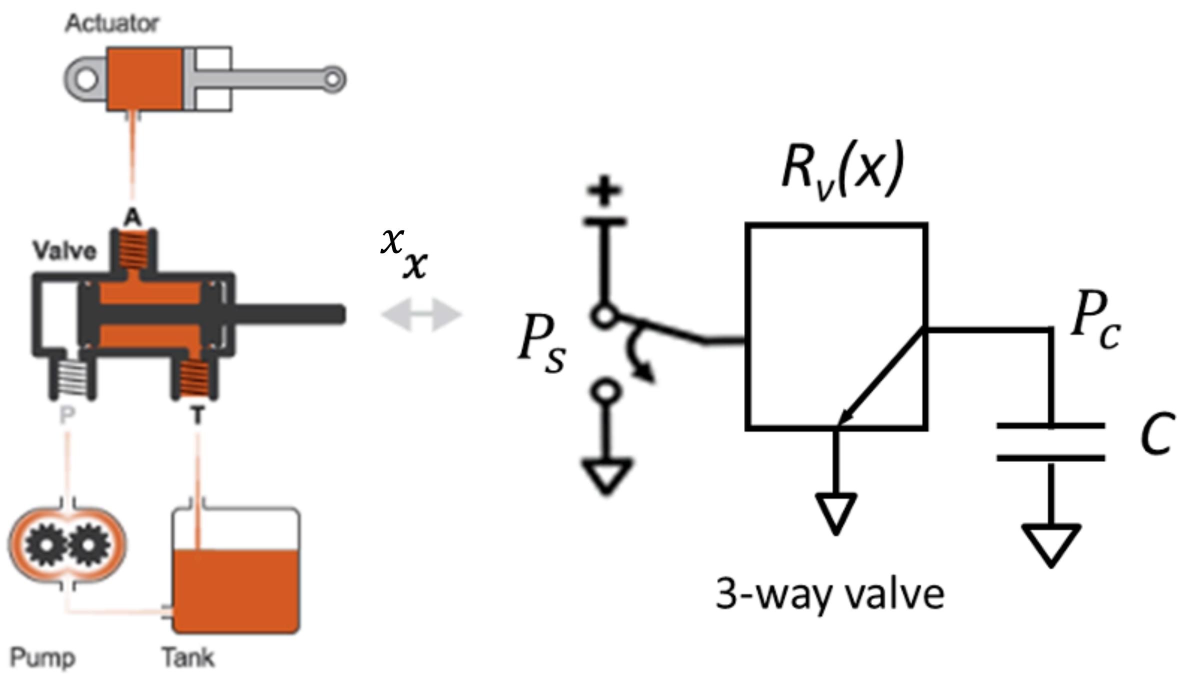


**Fig. 3: Fluidic RC model with Variable Orifice Resistance**

Fig. 3 depicts another example fluidic RC model that includes a variable orifice resistance. This model assumes that the valve has a rectangular cross-section, and that the valve spool followed a first order dynamics in time.

The orifice resistance as a function of displacement is governed by the equation:

$$R(x) = \frac{3.88e^{8}}{\frac{4A(x)}{\pi}}$$

and the valve displacement response by:

$$x(s) = \frac{x_{max}}{1 + \tau s}$$

Pressure gain data as a function of pressure and under different loads can be fitted to the example models described herein to derive valve parameters, e.g. valve cut-off frequency, that are independent of its fluidic cutoff frequency.

Techniques of this disclosure enable accurate characterization of a system, and enables users to accurately estimate valve performance under varied conditions.

## CONCLUSION

This disclosure describes determination of a fundamental cutoff frequency of a fluidic valve that is independent of its fluidic cutoff frequency. A fluidic test apparatus is set up connecting a fluidic reservoir to one or more fluidic valve(s) and an adjustable load. The valve(s) are switched on and off at a specified actuation frequency. The actuation frequency is adjusted and measurements are made over a range of different frequencies, e.g., about 0.1 Hz to about 500 Hz. Pressure gain as a function of frequency is determined over different fluidic loads and input pressures and is then utilized in conjunction with fluidic RC models described herein to determine an effective valve cutoff frequency that is independent of the different loads applied on the fluidic valve.