19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

A Novel Flow Control Valve for Pulsating Flows

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Abstract

The design and performance characteristics of a mass flow control valve to generate unsteady pulsating flows are presented in this paper. As the majority of the naturally occurring flows are pulsatile in nature, it becomes imperative to simulate these flows for their experimental analysis. The proposed flow control valve is capable of producing controlled, periodic pulsating mass flows having sinusoidal, triangular, and trapezoidal waveforms to be used for fluid dynamics research. The design of the valve, while being simple, allows for generation of pulsatile flows over wide range of amplitudes and frequencies. Distinct waveforms for the output flows, at two amplitudes and frequencies, are demonstrated experimentally, and compared with the conceptual design.

Introduction

Steady flows have been studied and investigated extensively in the history of fluid dynamics. However, steady flows do not occur in nature quite often. Most of the flows encountered in nature are inherently unsteady: cardiovascular flows in living organisms, atmospheric winds, ocean waves, flows due to propulsive mechanisms of flying and swimming organisms and flows in reciprocating and turbo-machinery. Experimental simulation of such flows for conducting research is possible only when pulsatile flows are fully realized in a laboratory environment. The motivation for the present work stems from the need to generate pulsating flows in controlled and repeatable modes having suitable waveforms. The unsteadiness manifests itself in the form of pulsations of mass flow rates of the fluid; air in this case.

Many attempts have been previously made to generate air flow pulsations for fluid dynamics and heat transfer studies. Cylinders with diametrically opposite circular holes rotating inside a pipe have been used to produce sinusoidal air flow variations [5, 7]. Such a configuration generates two pulses in one rotation of the cylinder. A similar pulsed profile is produced by a rotating butterfly valve installed in a straight pipe flow [2]. High output flow frequencies of about 50 – 100 Hz are possible from such rotatory flow valves depending on the maximum possible rotational speed.

Pulsating flow has also been obtained by an on-and-off air passage. In this method, circular plates or discs with radial slots make a vane type flow interrupter [3]. One of the slotted disc is fixed in the pipe, with its axis perpendicular to the flow, while the other rotates immediately upstream of it. Flow ejects when the slots overlap each other, and the geometry of the slots can dictate the on-and-off flow profile. An inherent limiting feature of these rotating valves and vanes is that the input and output mass flow rates remain almost the same, while the only variation in flows are in the form of velocity fluctuations.

Gas flows have been periodically oscillated by employing two spool-type servo valves connected to an isothermal gas chamber; one upstream and the other downstream [4]. The valves open and close periodically to generate sinusoidal mass flow rates but at low frequencies. A positive displacement valveless piston pump has also been used to create flow oscillations [6], but only very low output frequencies, less than 5 Hz, have been possible due to inertial effects.

A mass flow rate controller based on a nozzle at critical pressure conditions has been invented in [1]. The opening of the nozzle is controlled by an electrodynamic coil system and the output mass flow rate is directly proportional to the linear displacement of the coil. Various displacement profiles of the coil are capable of generating corresponding mass flow rate waveforms at high frequencies of around 125 Hz.

The objective of the present work is to generate waveforms of mass flow rates, namely sinusoidal, triangular and trapezoidal, but with much simpler design features of the valve that do not require critical pressures and electrodynamic coils for operation. The description of the mass flow control valve presented in the following sections outlines the innovative design features that bring out controlled and periodic output mass flow rates at various values of frequencies and amplitudes.

Conceptual Formulation

The design of the mass flow control valve is based on the fundamental relations of mass flow conservation and that the mass flow rate is proportional to the cross sectional area of the flow. Figure 1 shows a circular pipe of constant diameter with an axial inlet, and two opposite radial outlets. Let the inlet mass flow rate be M_i and the outlet mass flow rates be M_{o1} and M_{o2} through the outlet cross sectional areas A_{o1} and A_{o2} respectively.

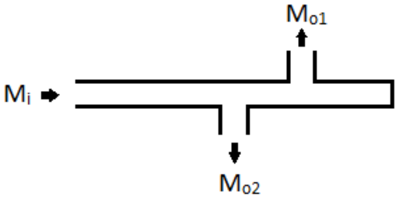


Figure1. Circular pipe with axial inlet and radial outlets

Based on mass flow conservation principle, at any instant during the flow,

$$M_i = M_{o1} + M_{o2} \tag{1}$$

We now introduce a dynamic attribute for the outflow cross sectional areas A_{o1} and A_{o2} as per the following.

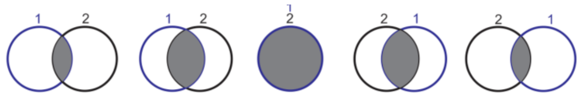
If A_{o1} is constricted by a certain measure in a given time, A_{o2} should open exactly by the same amount in the same time so that mass flows are always equal.

If this happens then the output mass flow rates will change with respect to the input mass flow rate, proportionally by the same amount as the cross sectional areas change, while always satisfying the mass flow conservation law. That is, as M_{o1} reduces due to decrease in A_{o1}, there will be an exactly similar increase in M_{o2} due to the same increment in A_{o2}. This results in the relation which states that the change in output mass flow rate in either of the two outlets is directly proportional to the change in the corresponding flow cross sectional areas.

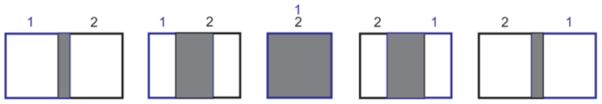
The above stated result is a simple corollary to the mass flow conservation principle, and forms the basis of the design methodology for the mass flow control valve, which is presented in the following section.

Design Methodology

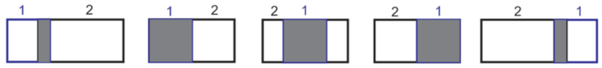
Mass flow pulsations are created by changing outlet flow cross sectional areas in an alternating and periodic way. This amount of change will proportionally alter the magnitude of output mass flow that exits the effective cross-sectional area. The changes in shape of the effective cross-sectional areas will determine the waveform of the output mass flow. This can be explained using figure 2.



a. Circular orifice 1 traversing circular orifice 2



b. Square orifice 1 traversing square orifice 2



c. Square orifice 1 traversing rectangular orifice 2

Shaded regions are the overlapping cross sectional areas through which flow passes

Figure 2. Effective cross-sectional areas for output mass flows

Figure 2(a) shows the passage of circular orifice 1 with respect to circular orifice 2 in a given air flow; the flow is assumed to be normal to the plane of the figure. As the orifices sweep, the shaded regions form the effective cross-sectional areas for the flow to pass through. These effective cross-sectional areas change in a sinusoidal way, as shown in figure 3(a), as the orifices open and close. The mass flow then effusing out of these areas would also vary in a sinusoidal manner based on the earlier formulated corollary.

A similar scenario as above, but for two square orifices is depicted in figure 2(b). As the square orifices transit with respect to each other, the intersecting areas increase and decrease linearly. This gives a triangular variation for the effective cross-sectional areas, see figure 3(b), and would thereby impose the same for the output mass flows.

The effective cross-sectional areas can be made to change in a trapezoidal fashion by making a square orifice traverse a rectangular orifice as shown in figure 2(c). As the square orifice begins to intersect the rectangular orifice the overlapping area increasing linearly until the square orifice completely spans itself over the rectangular orifice. The intersecting area would then be constant till the square orifice begins to exit the rectangular orifice, after which the overlapping area will fall. This leads to a trapezoidal waveform for the effective cross-sectional areas, as illustrated in figure 3(c), and would imply the same for the output mass flows.

The waveforms for the effective cross-sectional areas A_{eff}, as the respective orifices traverse each other, in the three scenarios are shown in figure 3. The areas have been normalised with respect to the area of the travelling orifice 1 A_1. The output mass flows through these would then take the same time dependent profiles as the corresponding orifice configurations. The physical arrangement of these orifices as ports in the valve is explained in the next section.

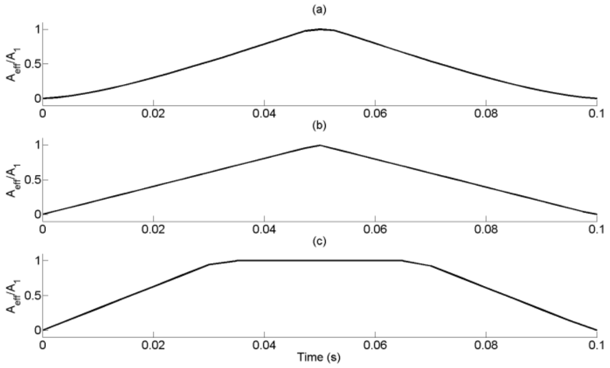


Figure 3. Variations in the effective cross-sectional areas (a) Sinusoidal – circular orifices (b) Triangular – square orifices (c) Trapezoidal – square and rectangular orifices

Valve Schematics

Employing the methodology elucidated in the preceding section, a mass flow control valve which produces pulsating flows has been designed and fabricated. A two-dimensional schematic of the valve is shown in figure 4. The valve consists of two hollow cylinders, with one cylinder rotating concentrically inside the other. Compressed air flow is fed axially into the inner cylinder and it exits the outer cylinder radially.

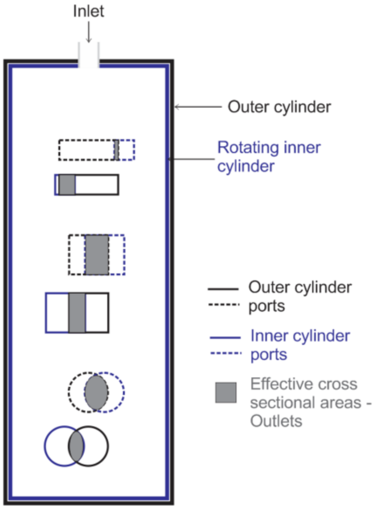


Figure 4. Schematic of the mass flow control valve

As shown in figure 4, two ports, in each set of circular, square and rectangular cross sections, have been made on the surface of the outer cylinder. The solid line ports are facing the reader while the broken line ports are into the plane of the figure. A similar set of ports, of circular and square cross sections, are bored on the surface of the inner rotating cylinder. These inner ports are made to match concentrically with the outer ports.

As the inner cylinder rotates one of the two inner ports in each set starts overlapping the respective outer port and thereby increases the intersecting area for the outflow through these ports. The other opposite inner port simultaneously begins to depart from the respective outer port and reduces the overlapping area for the flow to exit radially. As remarked previously, these overlapping (intersecting) areas are the effective cross-sectional areas through which flow exits and as they change the output flow undergoes pulsations. The areas are represented as the shaded regions in figure 4.

The annular clearance between the inner and outer cylinders is made such that there is minimum clearance provided to ensure rotation of the inner cylinder. Pulsating flow then can be obtained from either of the two outer ports in each set. The frequency of pulsation is governed by the number of inner ports in each set and rotational speed of the inner cylinder. The amplitude of pulsation is controlled by changing the amount of inlet mass flow. The next section describes the experimental setup followed by the pulsating flow results.

Experimental Setup

The layout of the experimental set up to demonstrate the proof of concept is shown in figure 5. Compressed air supply conditioned through an air filter and pressure regulator is fed to the air receiver tank and maintained at 2.75 bar. Compressed air from the receiver tank is then delivered to the mass flow control valve with the help of a needle valve, which is used to control the inlet mass flow rate. This flow rate is indicated by a flow meter installed downstream.

The pulsating flow obtained from the control valve is characterized for the measured velocity data obtained from a TSI™ IFA-300 Constant Temperature Anemometer. Data from the system is transferred and analysed in a desktop computer with the help of an analog-digital board. Hot-film probes, supplied by TSI™, are placed at the outer cylinder ports and measure the output pulsating flow velocities. The inner cylinder is rotated with the help of variable drive assisted electric motor. When performing experiments for measuring the pulsating flow velocities for a given profile from the valve, the other two profile outlets were closed.

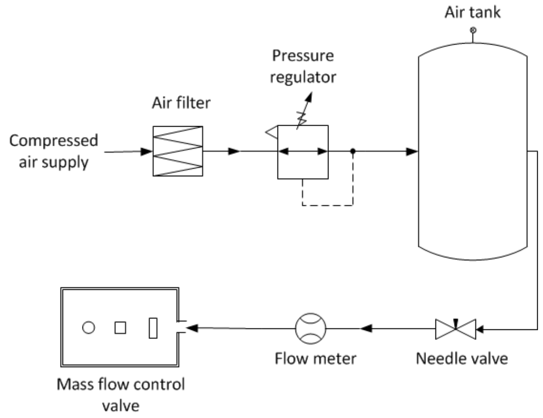


Figure 5. Pulsating flow experimental setup

Pulsating Flow Results

Measurements obtained for frequencies of 20 Hz and 50 Hz at different velocity amplitudes are presented in this paper. The measured output pulsating flow velocities V_m are plotted with the conceptual output velocity profiles V_c. These conceptual signals are generated numerically from the output mass flow variations as the orifices cross each other; they do not take into account the inertial and viscous effects of the fluid.

Figures 6 and 7 show the hot-film velocity measurements for sinusoidal pulsating flows at 20 Hz and 50 Hz respectively, at two different velocity amplitudes. The comparison of the measured velocity pulsations with the conceptual flow variations shows acceptable similarities with amplitude deviations within 1 – 1.6 m/s.

The triangular pulsating flow profiles at 20 Hz and 50 Hz are illustrated in figures 8 and 9 respectively. The trapezoidal pulsating flow profiles which depict a step change in the flow are shown in figures 10 and 11 for frequencies 20 Hz and 50 Hz respectively,

As mentioned earlier, the conceptual pulsating flow variations do not completely model the fluid flow through the valve and this leads to some departures of the measured flow from the calculated flow profiles. In addition, the imperfections in the valve axial alignment, the geometrical precision of the orifices and the clearance between the cylinders which cause flow leakage also contribute to some offsets in the measurements.

For instance, the presence of harmonics in the trapezoidal pulsating flow and variations in velocity amplitudes are a result of these factors. The differences between the conceptual and measured values also seem to increase at higher frequencies, in the cases of triangular and trapezoidal pulsating flows.

Despite the above mentioned drawbacks, the pulsating flow profiles match satisfactorily with the design outcomes. The flow control valve being the first prototype of its kind, the pulsating output flow from it can be made more refined and accurate by rectifying the existing faults.

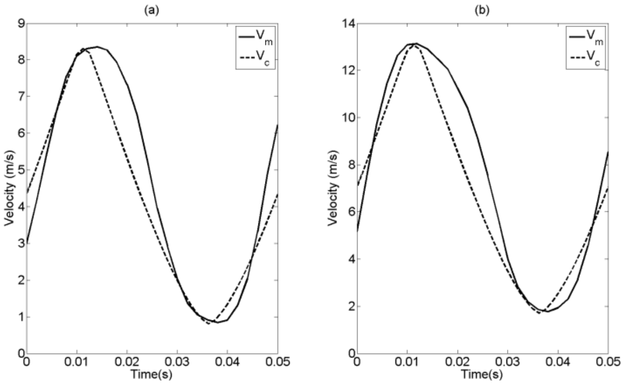


Figure 6. Sinusoidal flow profiles at 20 Hz for velocity amplitudes of (a) 4 m/s and (b) 6 m/s

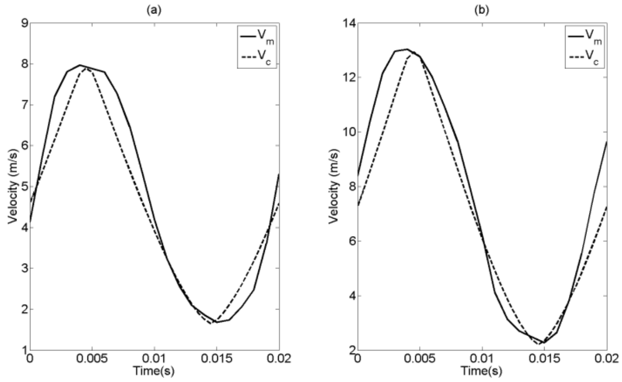


Figure 7. Sinusoidal flow profiles at 50 Hz for velocity amplitudes of (a) 4 m/s and (b) 5 m/s

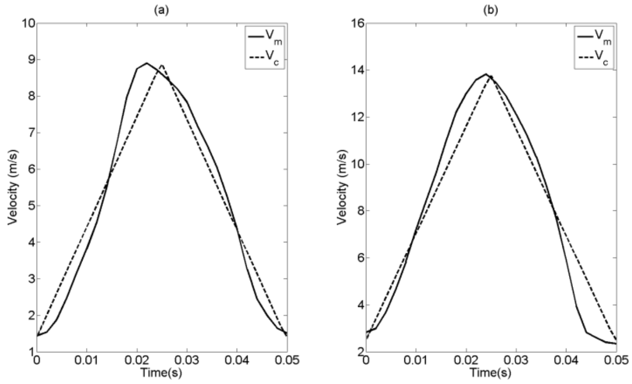


Figure 8. Triangular flow profiles at 20 Hz for velocity amplitudes of (a) 7 m/s and (b) 11 m/s

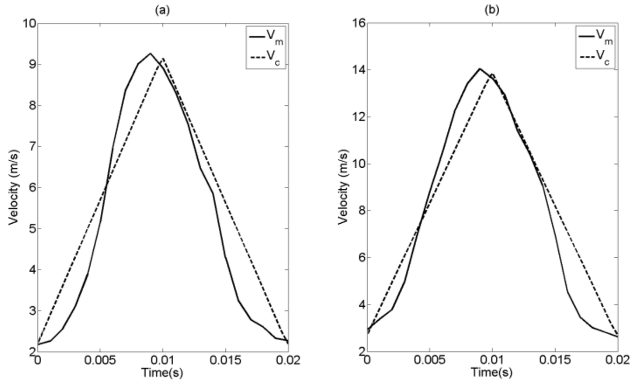


Figure 9. Triangular flow profiles at 50 Hz for velocity amplitudes of (a) 7 m/s and (b) 11 m/s

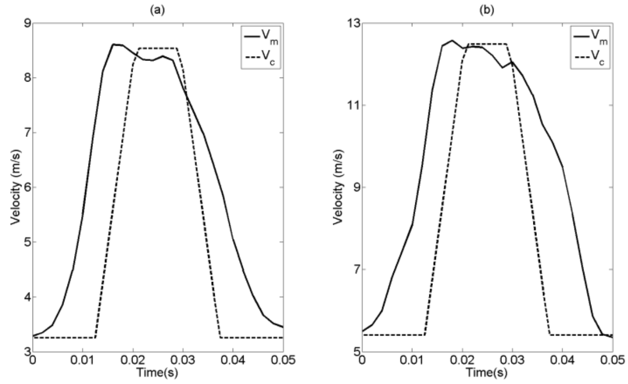


Figure 10. Trapezoidal flow profiles at 20 Hz for velocity amplitudes of (a) 5 m/s and (b) 7 m/s

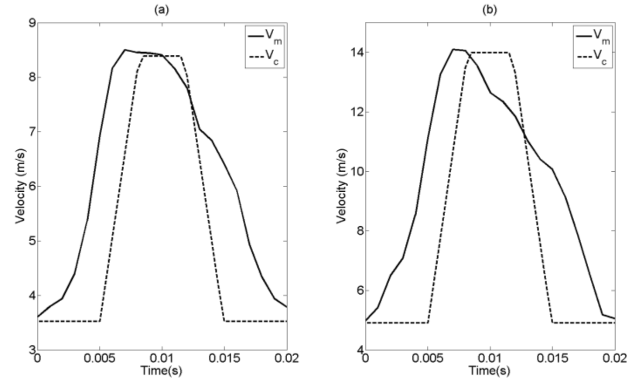


Figure 11. Trapezoidal flow profiles at 50 Hz for velocity amplitudes of (a) 5 m/s and (b) 9 m/s

Conclusions

The output waveforms demonstrate the capability of the flow control valve to produce pulsating mass flows. The novelty of the control valve is evident from the simplistic yet effective and innovative design that produces three forms of pulsating mass flows in a single instrument, without the use of any specialised components or critical flow conditions. Output from this flow control valve can used to investigate unsteady and pulsating flows in both the laminar and turbulent flow regimes.

Although the output pulsating flow waveforms match less closely with the conceptual flow variations, the former do exhibit similarities to the expected design outcomes. Efforts are presently being made to improve the pulsating flow profiles while eliminating the design drawbacks. Future work is also aimed at producing pulsatile flow over wide ranges of amplitudes and frequencies in addition to making the valve more versatile, robust and repeatable in its output flow profiles.

Acknowledgments

The authors graciously acknowledge the ARC Discovery Project Grant DP 130103271which has made this research work possible. We are also thankful to the technical team spearheaded by Mr. David Collier at Curtin University for in-house fabrication of the mass flow control valve.

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