# Conceptual Designing and Numerical Modeling of Micro Pulse Jet for Controlling Flow Separation

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**Abstract:**

A conceptual design and numerical model of Micro Pulse Jet has been developed to investigate the flow separation. This valve is designed to generate the stream line vortices to suppress the flow separation by enhancing the mixing of the flows between free stream and separated flow of the boundary layer through pitched jet orifice of very small width. This paper describes not only the conceptual modeling of Micro Pulse Jet but also presenting the numerical analysis and results of steady and unsteady pulse of micro jet. The unsteady pulse of the valve is simulated by the periodic inlet boundary condition through a mathematical model. A 2-D ramp with 20 degrees divergence is selected. The divergence of the lower wall of the ramp is large enough to produce a strong adverse pressure gradient causing the boundary layer to separate. A jet orifice is introduced at the upstream of the divergent portion of the ramp and the effect of steady and unsteady jet is analyzed. The main inlet boundary condition is almost of 0.2 Mach. The jet amplitude is characterized by the velocity ratio ($V_j/V_\infty$) in between 0 to 5 and the jet pulse frequency is varying between 0 to 100 Hz. A comparison between the steady and unsteady Micro Pulse Jet is also done, which indicates the mass flow requirement for pulse micro jet is reduced significantly as compare to the steady jet for the flow separation control.

**Keywords:** Vortex Formation, Mixing Enhancement, Flow Separation, Pulse Frequency, Pressure Ratio, Pitch Angle, Mass Flow Rate, Unsteady and Steady jet, Periodic Behavior

## 1. INTRODUCTION

Now a day's flow separation control mechanism is largely in practice to enhance the performance of the system in design and off design condition. Generally on the basis of the working principle the flow separation control techniques are classified as Passive and Active control method. In passive control method there is no external source required while there must be an external source for separation control in Active flow control method [1].

The main disadvantage of the passive control method is associated with larger drag value and unable to correspond in time varying action requirement while on the other hand active control method is quite capable of producing good results in design and off design condition. In active flow control technique where separation is controlled by the pulse of the jet, a jet is introduced at the upstream of the effected flow region and the separation is controlled by the jet vortex [2]. The generated vortex enhances the mixing of the flow between the high energy free stream and the low energy separated boundary layer flows [3, 2].

The basic purpose of introducing the new conceptual approach of Micro pulse Jet is to analyze the strength of emitting jet from the valve in order to capture the flow separation effectively. There are many advantages of new conceptual model of Micro Pulse Jet over the traditional methods e.g. it has compact size which can be easily stowed in any system like in internal flows and turbo machinery application, working principle of unsteady valve is very simple and unsteady pulse jet created by the valve having high mach.

In the present study the Micro pulse jet is used for effective control of the flow separation. The conceptual model is applied and analyzed by numerical model of the valve. The unsteady pulse of the jet through the valve is simulated by the periodic inlet boundary condition through mathematical model. The basic working principle of the valve is based on the pressure ratio values. The difference between the total pressure at the lower surface and the static pressure at the upper surface of the valve is providing driving force for unsteady pulse jet. This pressure ratio is responsible for controlling the amplitude of the jet and also defines the velocity ratio. Research starts with conceptual design of micro pulse jet. Two test configurations are devised configuration A and configuration B on the basis of pitch angle.

## 2. REVIEW OF RELATED RESEARCH WORK

Previous research work for flow separation control is done by the following methods.

- Tangential blowing and suction method. The basic disadvantage of this technique is associated with an external source to avoid the flow separation which increase the complexity level of the system and also increase the parasitic drag value.
- Vortex generators (VGs and Micro VGs) the basic disadvantage of this method is related with larger value of parasite drag as compare to other active flow control techniques [4].
- Acoustic Excitation and It's effect has been observed in delaying the separation and it is well known documented by several researcher like (e.g. Collins & Zelevitz 1975;Mueller & Batill 1982; Ahuja & Burrin 1984 near stall condition was carried out by the group at Lockheed [5]). The main disadvantage of Acoustics excitation is incapable of producing excitation of large intensity for controlling the flow separation. Moreover, these acoustic excitation studies were in most cases facility dependant and therefore, it is of limited use from a practical perspective.
- Synthetic Jet Actuator (SJA) which is based on "zero-net-mass flux flow" in which the energy can be transferred to the flow without adding extra mass [6-10]. The main disadvantage of this method is associated with the strength of jet in small configuration.

Basically all the above techniques are not able to produce a jet of higher energy to suppress the flow separation in highly turbulent and separated environments. This phenomenon is quite evident in AEROMEMS-I and some preliminary work done in AEROMEMS-II in which it was observed that SJA while operating in self contained zero-net–mass-flow mode is not able to produce a jet of velocity of 100 m/sec in small configurations [11]. This problem leads to the importance of Pulsed Jet Actuators [12-14], but in pulse jet actuator there must be an external source for producing pressurized air to open the valve and control the flow separation. In the present research work there is no need of external source for producing the jet. This concept is based on pressure gradient in which total pressure at the lower surface of the valve is greater than the pressure at the upper surface and consequently separation is controlled through the unsteady pulse of the jet.

## 3. CONCEPTUAL DESIGN OF MICRO PULSE JET

The conceptual model of Micro Pulse Jet is mainly consists of two parallel plates having pores and voids for the jet. The plate (5) moves over the stationary pate (6) through the force provided by the driving member (10). The driving member is activated by some external source like electric current. The working principal of the valve is based on the pressure gradient between the lower and at the upper surface of the valve. When the pores are aligned with each other due to the motion of moving plat over the fixed plat, gives the passage for unsteady pulse jet. The unsteady jet is further accelerated in convergent duct in the form of nozzle, as shown in the fig [1].
The conceptual model of the valve is shown in fig [1] and due to simplicity of the design and its compact configuration; it can be easily accommodated in any system. The basic principal of separation control through unsteady jet is shown in fig [2].

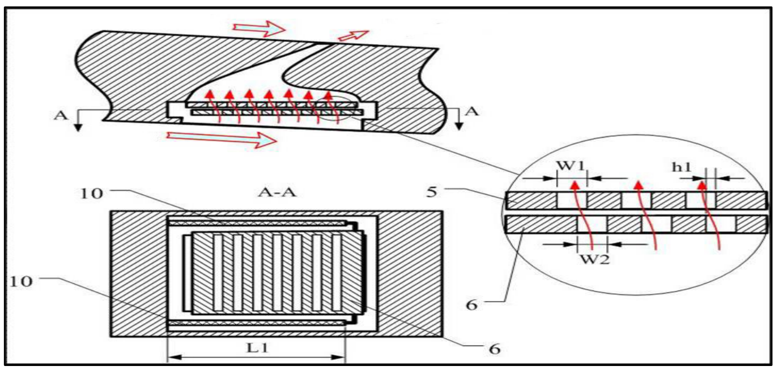



**FIGURE 1:** Conceptual model of Micro Pulse Jet

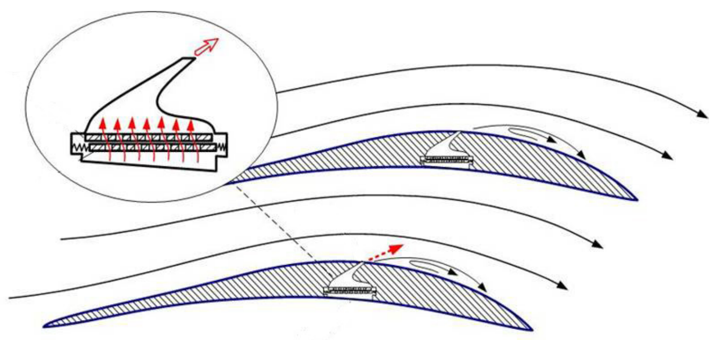


**FIGURE 2**: Conceptual Model of Flow Separation Control by Micro Pulse Jet

## 4. MODELING OF FLUID DYNAMICS

A computational study has been carried out in order to investigate the effectiveness of the conceptual model in controlling the flow separation. The unsteady valve is simulated by the periodic inlet boundary condition though CFD-ACE+ software. In order to validate the new conceptual model of micro Pulse Jet, a 2-D ramp channel is selected due to severe separation in the flow, caused by existence of adverse pressure gradient due to the lower wall divergence of the ramp channel.

### 4.1 Case Discription

2-D channel with 20 degrees of divergence is selected for numerical analysis of Micro Pulse jet. The jet of 2mm is placed at the upstream of ramp. The jet amplitude is varied by using various value of K. The various velocity ratios have been analyzed with different pitchy angle (α) and jet pulse frequency. The reference case for the validation, with and without the valve is shown in the following figures.

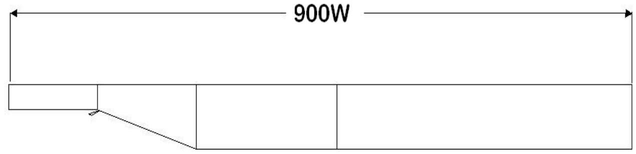



**Figure 3:** Baseline case geometry

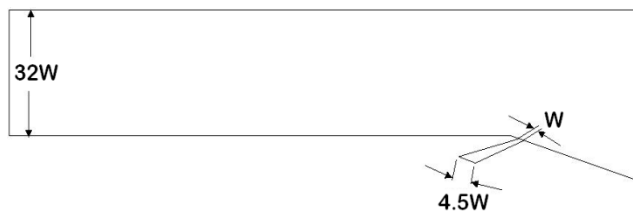



**FIGURE 4:** Baseline case geometry with valve

### 4.2 Mesh

2-D ramp is descritised with H- type structured mesh with almost 100,000 mesh cells. The RNG K-E turbulence model is used with viscous spacing of 1e-05 in order to keep the Y+ values in between the recommended values for capturing the flow separation and unsteadiness of the flow. The mesh of the ramp channel with unsteady valve is shown in the fig [5].

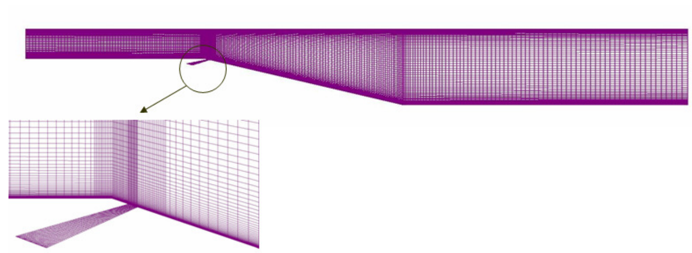


**FIGURE 5**: Mesh of 2-D ramp with almost 100,000 cells

### 4.3 Boundary Condition

In order to simulate Micro Pulse Jet with the Ramp 2-D model four types of boundary conditions are used. Inlet with Mach no. 0.2 is used for the free stream condition, at the end of the ramp the Outlet fixed pressure is used while the ramp has no slip wall condition. The valve is simulated through periodic Inlet boundary condition having transient normal total pressure condition as shown in mathematical model

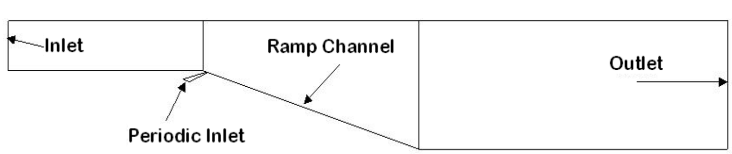



**FIGURE 6:** Detail of Boundary Condition

### 4.4 Mathematical Model

Basic purpose of this research is to simulate the valve for generating the micro pulse jet for controlling the flow separation. The functionality of the valve which consists on a converging duct is based upon the pressure gradient between the lower surface and the upper surface of the

valve. The flow is accelerated due to the pressure gradient and the convergent duct of the valve. The Mach of the jet and velocity ratio is controlled by the pressure ratio (K).
The transient behavior of the valve is modeled with the help of the mathematical model. The following mathematical function is used to simulate the valve with periodic inlet boundary condition for the unsteady micro pulse Jet.

$$P_O = P_{st}[(\frac{\cos wt + 1}{2}) * K + 1] \qquad [1]$$

Where K is the pressure ratio factor

## 5. EXPERIMENTAL VALIDATION

The present research work is based on computational analysis of a new conceptual design of the valve through periodic inlet boundary condition by using above mentioned mathematical model. So, it is mandatory to validate the computational scheme and discritization methodology through some experimental work. As this research work is based on new conceptual approach so for validation purpose a 2-D ramp case is selected having the experimental results available in ref [2]. In order to correlate the numerical results with the experimental data, the same environments of experimental conditions are tried to simulate with inlet velocity of 11.5 m/sec only. New conceptual model of the valve is analyzed with different inlet conditions. The non dimensional velocity ratio at various points as shown in fig [7], plotted against wind tunnel data shows good agreement. Dimensions are in cm.

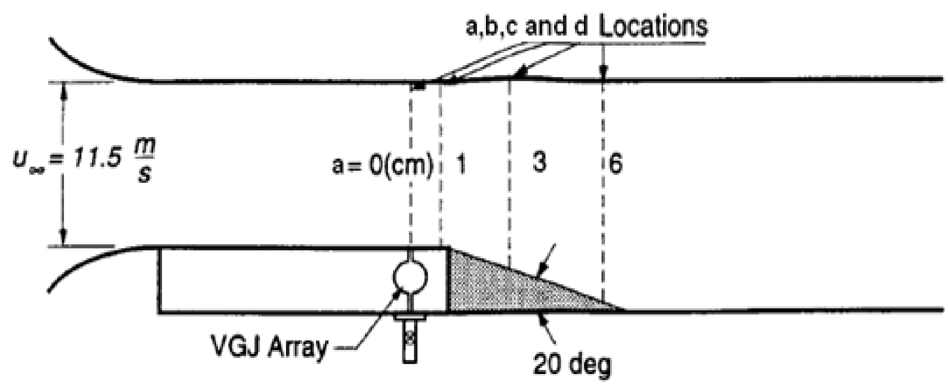



**FIGURE 7:** Experimental setup and Position of Velocity Profiles
(Reprinted with permission from American Institute of Aeronautics and Astronautics (AIAA))

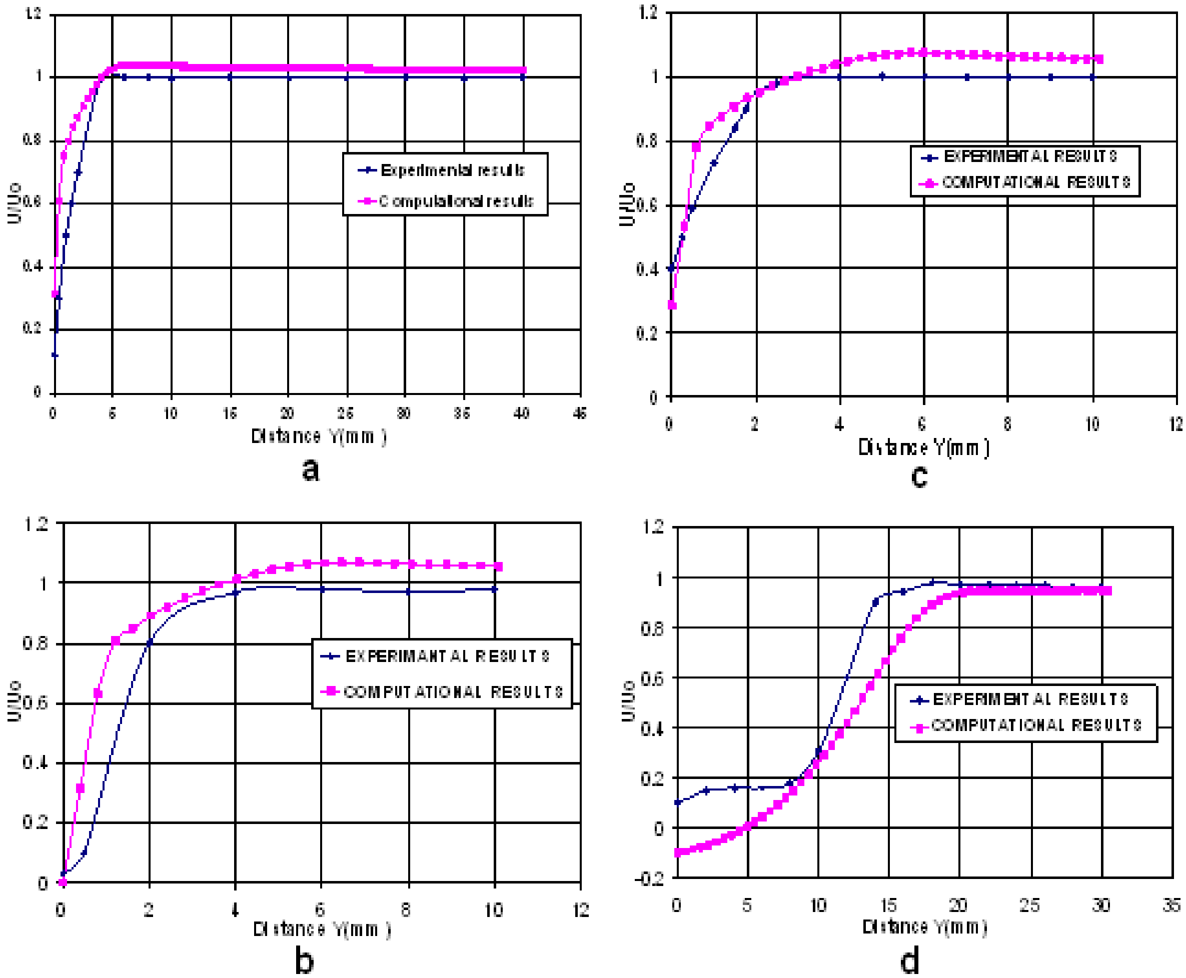



**FIGURE 8:** Velocity profile at various locations
(Experimental data reprinted with permission from American Institute of Aeronautics and Astronautics (AIAA))

The trend line of velocity ratio shows a good agreement of computational results with experimental. Overall the percentage variation in the results is less than 10%. The behavior of velocity ratio depicts the presence of separated boundary layer adjacent to the lower wall of ramp as shown in fig [8(d)], where Uo is inlet velocity (11.5 m/sec) is selected for correlation purpose only while the rest of research work is conducted at Mach 0.2.

## 6. BASELINE FLOW FIELD CHARATESISTIC

A baseline analysis shows that the flow has high turbulent separated structure near the lower wall of the ramp channel, due to the adverse pressure gradient. The behavior of v component of velocity contour shows that the flow is not attached with the wall. The rotating vortex in without valve configuration is not able to overcome the separation in the flow, as there is no mechanism of crating unsteady pulse jet, as shown below.

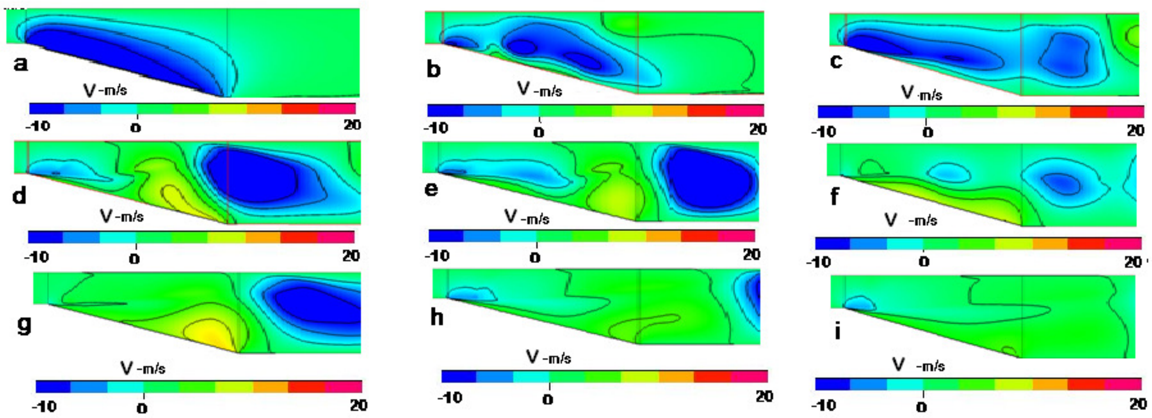



**FIGURE 9:** Velocity v-contour at (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The results of Velocity (v) contour clearly describe the existence of separation with the lower wall of the ramp channel. The rotating vortices is not able to control the separation in the flow rather the separation is growing with time, as shown by the behavior of the stream traces in the following figure[10].

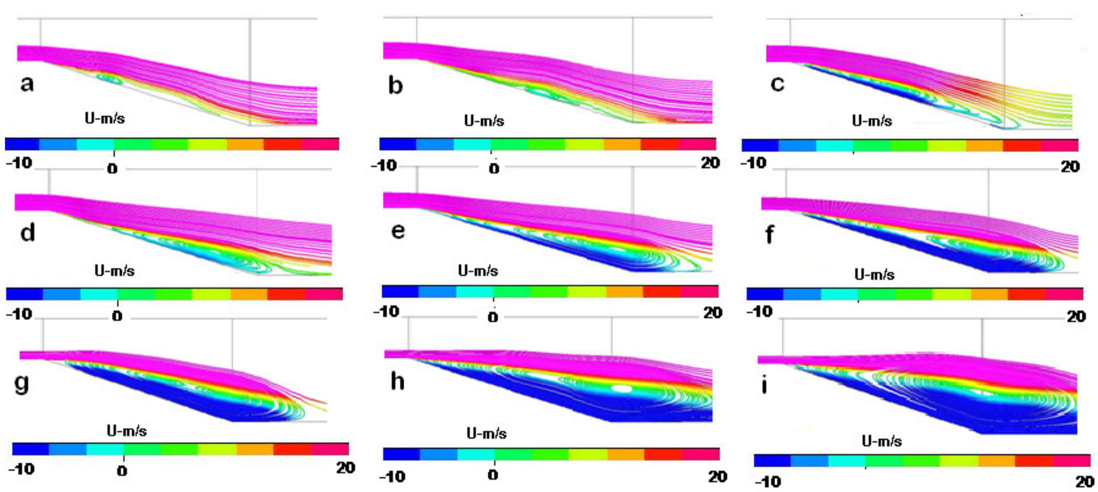



**FIGURE 10:** Velocity u traces at (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec. (e) Time=0.05 sec, (f) Time=0.06 sec,(g) Time=0.07 sec, (h) Time=0.08sec (I)Time=0.1sec

The stream traces of x component of velocity (u) show the flow behavior at various time intervals. The separation is growing with time in without control environment as shown by the following [10].

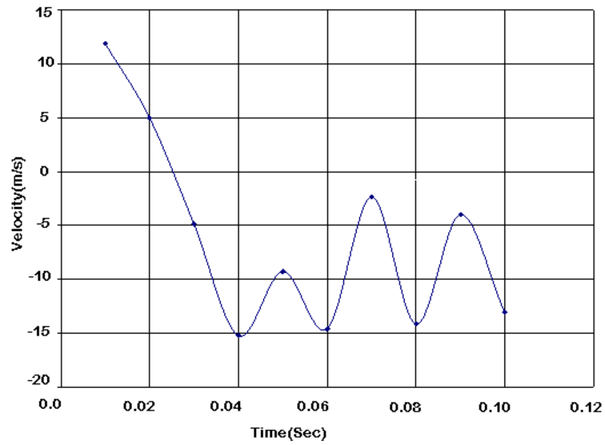



**FIGURE 11:** Velocity plot at various time intervals

The periodic behavior of the separation is observed at almost 72% ramp channel length, as shown in the fig [11]. The magnitude of the velocity clearly indicates the existence of the separation in the flow.

In order to estimate the frequency of separated flow, various points are introduced at different location in the computational domain of the ramp channel and it was investigated that the unsteady flow has the frequency of 40 HZ.

## 7. EFFECT OF MICRO PULSE JET ON FLOW SEPARATION

The effect of Micro pulse jet on flow separation is investigated with the various test parameters including different velocity ratio (VR), pitch angle (α) and various set of unsteady pulse frequencies. The flow characteristics under the control environment of Micro pulse Jet valve operating at various combinations of test parameters are analyzed with the help of the following table.

| Test Configuration | VR | Pitch Angle (α) | Unsteady Frequencies (HZ) |
|---|---|---|---|
| A | 2.3 | 45 | 20,40,80,100 HZ |
| | 2.5 | 45 | 20,40,80,100 HZ |
| | 3 | 45 | 20,40,80,100 HZ |
| B | 2.3 | 30 | 20,40,80,100 HZ |
| | 2.5 | 30 | 20,40,80,100 HZ |
| | 3 | 30 | 20,40,80,100 HZ |

**TABLE 1:** Test parameters for Micro Pulse Jet

### 7.1 Flow Visualization and Results

The results from all above mentioned configuration will discuss in this section. The results are described on the basis of velocity contour, flow quality which shows the separation existence, mass flow requirement to control the flow separation at steady and unsteady jets and velocity plots at various points in the flow field. For the flow visualization and qualitative results the best combination of pitch angle with different velocity ratio and frequencies are selected. Overall four test configuration are selected which include the worst and the best combination of pitch angle and different frequencies at two different velocity ratios.

### 1. Test configuration (A)

The test configuration A has the combination of different velocity ratio, constant pitch angle and various set of frequencies, from these test configurations on the bases of the quality of the results the two cases are selected for the results discussion in the following manner.

#### a) Results (VR=2.3, $\alpha$=45$^{O}$ )

Micro Pulse Jet operating at above mentioned test parameters are analyzed in detail. This section of paper restrain the flow characteristics results in the form of velocity contours and stream traces through the pulse jet valve at unsteady frequency of 80 HZ. The unsteady pulse frequency of the jet is selected on the basis of the quality of the results.

When the Micro Pulse valve is operating with the combination of pitching angle 45 degrees, velocity ratio 2.3 and the pulse frequency 80 HZ, the results of velocity contour and the stream traces show that the valve is not able to control the flow distortion effectively. The results of stream traces are described below,

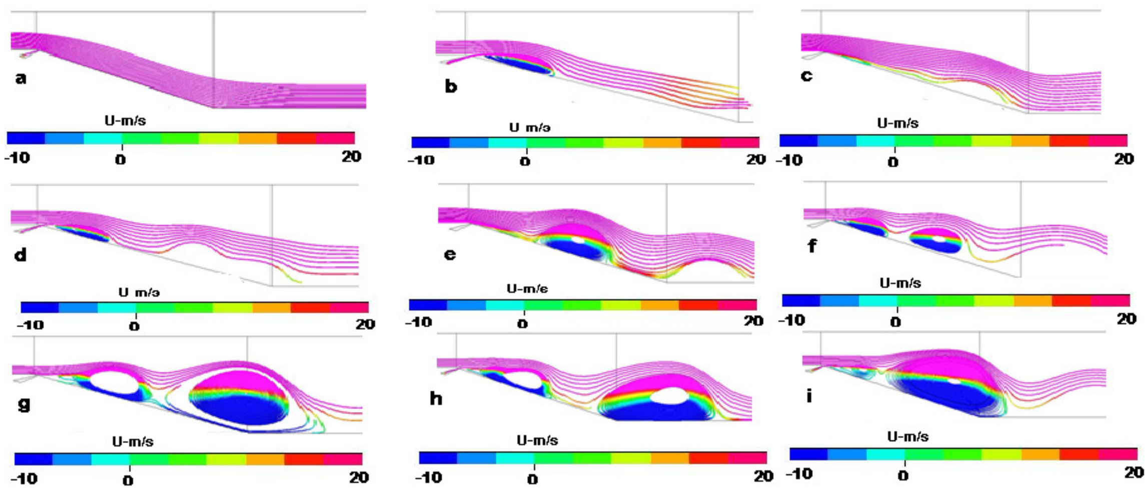


**FIGURE 12:** Velocity u traces at pitch angle=45, VR=2.3 and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

Initially it was investigated that due to the pulse of the jet, separation is removed by the rotating vortex. There is a small portion of the separated flow just under the pulse of the jet, when the valve is operating at 80 HZ, as shown in fig [12(b)]. The separation in the flow is growing with the passage of time as shown in fig [12(c) and (d)]. Actually the valve is creating the rotating vortex continuously and the separation is controlled to some extent at the initial level of time interval, as shown by the fig [12(a) to (c)]. There is a severe separation observed at the time interval of 0.05 sec of the simulation as shown by the fig [12(e)], it may be due to the jet operating angle or the velocity ratio which is not allowing the unsteady jet to control the separation in the flow in an effective manner. This phenomenon of controlling the flow separation and internal flow behavior is also visible in the velocity contour plot as shown in the following figures,

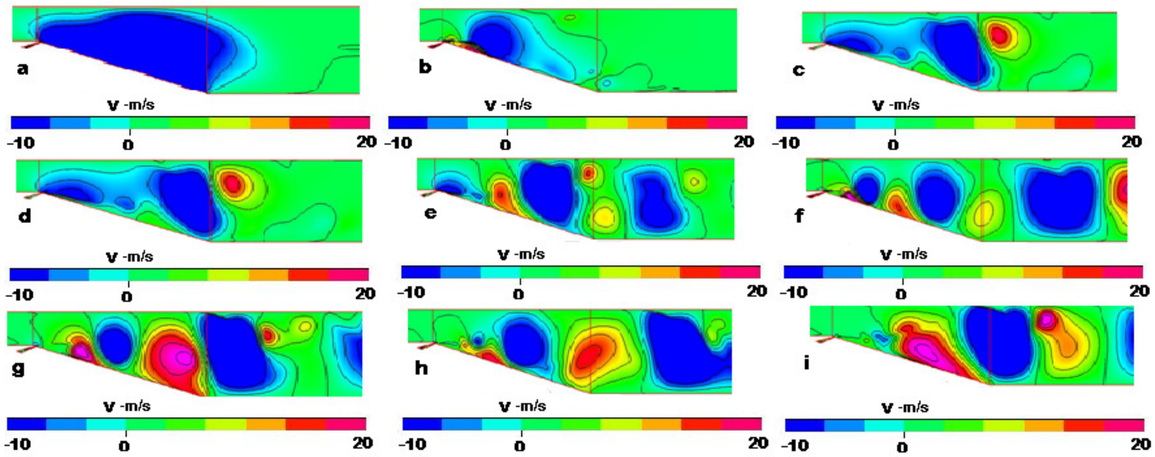
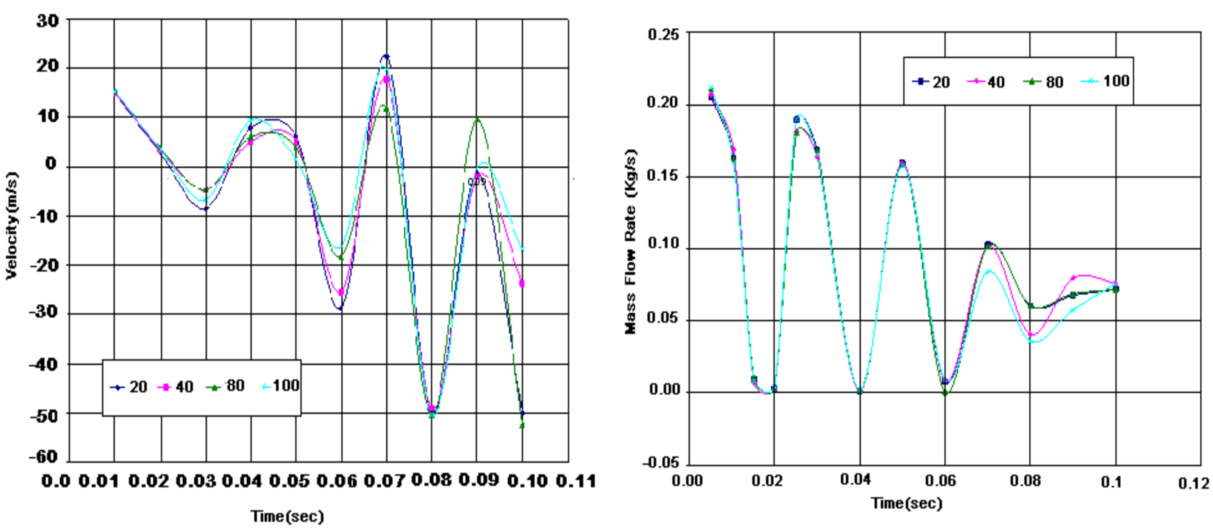



**FIGURE 13:** Velocity v-contour at pitch angle=45, VR=2.3 and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The significance of created rotating vortex for controlling the flow separation is quite visible in velocity contour plot. There is a visible separation in the flow at the time of 0.05 sec as shown in the fig [13(e)]. The valve operating at 80 HZ is not capable of reducing and removing the separation in the flow along the wall of the ramp rather the effected portion is growing and separation becomes more and more severe with the time.

In order to investigate the effective control of the separation by the unsteady pulse jet operating at test configuration (A), the data of velocity are obtained at a point almost 72 % downstream of the ramp channel.




(a) (b)

**FIGURE 14:** Plots at (VR=2.3, α=45) (a) Velocity plots at 72 % ramp length, (b) Mass flow rate requirement at various frequencies of 20,40,80,100 HZ.

The periodic behavior of velocity plot clearly indicate that in the beginning the separation is controlled by the pulse of the jet while operating at velocity ratio of 2.3 and at a pitch angle of 45 degrees but with the passage of the time the magnitude of the velocity even at higher frequencies becomes negative, indicates the existence of separation in the flow as shown in fig [14(a)].

Mass flow requirement for the valve to control the separation is also plotted in fig [14(b)] which shows there is no significant difference between the mass flow requirements at various frequencies. It was investigated that the mass flow requirement for the steady jet is significantly larger as compare to the unsteady frequencies in order to capture the flow separation in the flow.

**b) Results (VR=3, α=45 $^O$)**

The results for the test configuration at Pitch angle 45 degrees with the velocity ratio 3, shows the effective control of Micro Pulse Jet as compare to the unsteady pulse jet operating at velocity ratio 2.3. The pulse jet of the valve is controlling the flow separation quite effectively while operating at 80 HZ. The flow behavior under the control action of Micro pulse Jet is shown by the following figure

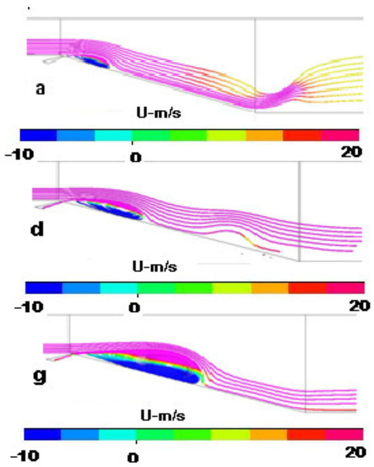



**FIGURE 15:** Velocity u-contour at pitch angle=45, VR=3and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The flow picture under the control environment of micro Pulse Jet operating at above mentioned parameters show that the valve is quite capable of controlling the separation in the flow. The pulse of the jet is not allowing the separation to grow with time as shown by the fig [15 (a) to (i)]. The same phenomenon is also quite evident from the velocity contour plot, as shown by the following figure.

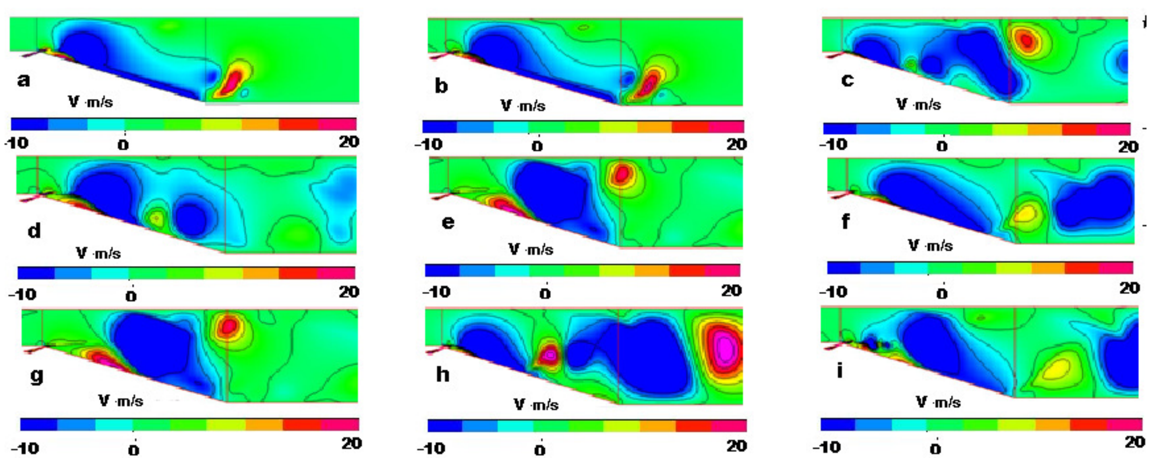
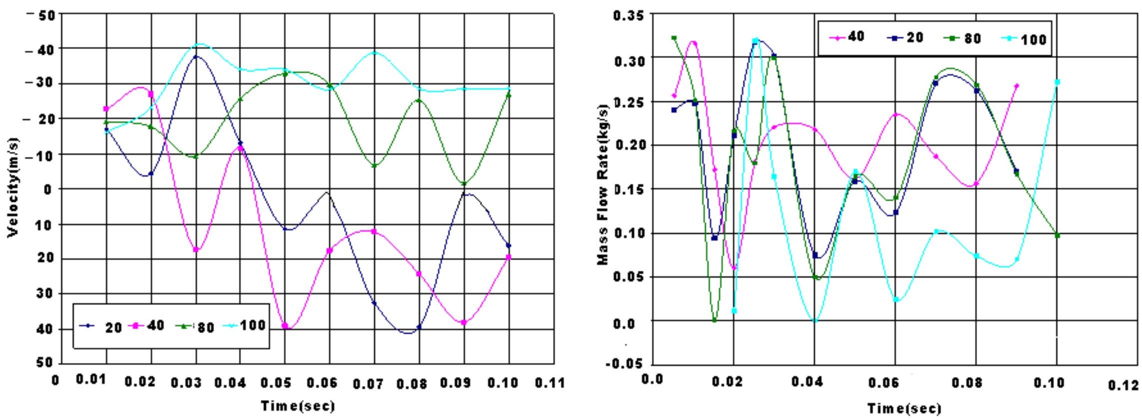



**FIGURE 16**: Velocity v traces at pitch angle=45, VR=3and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The effectiveness of the unsteady pulse frequency in controlling the flow separation is quite visible in velocity contour plot, shown in fig [16]. Overall the flow characteristics in term of separation control for the unsteady jet operating at velocity ratio 3 at constant pitch angle and unsteady frequency of 80 HZ is better than the velocity ratio 2.3.

The velocity plot at the 72 % downstream length of the ramp channel shows that the valve is quite capable of controlling the separation at 80 HZ in an efficient manner as compare to the unsteady jet operating at same pitch angle with the velocity ratio 2.3, as shown by the periodic behavior of velocity in fig [17 (a)].




(b)

**FIGURE 17:** Plots at (VR=3, α=45) (a) Velocity plots at 72 % ramp length, (b) Mass flow rate requirement at various frequencies of 20, 40, 80,100 HZ

The mass flow rate requirement while operating with these parameters, is significantly increase as compare to the previous test parameters case as shown in the fig [17(b)], but having the lesser requirement for the unsteady case as compare to the steady jet operating under the same test parameters of configuration (A).

### 2. Test configuration (B)

A detailed numerical study has been conducted to investigate the effectiveness of Micro Pulse Jet operating at test condition, described in configuration B. Two test cases are selected on the bases of the results obtained at constant pitch angle 30 degrees, different velocity ratios and with the same unsteady jet frequency of 80 HZ, in the following manner.

#### a) Results (VR=2.3, α=30 $^{O}$)

It is investigated through comprehensive numerical study that the unsteady Micro Pulse Jet operating at pitch angle 30 degrees, velocity ratio 2.3 and with the unsteady frequency 80 HZ, controlling the separation in the flow quite effectively. Overall results obtained from the flow visualization and the velocity plot at a certain point, downstream of the ramp show that the pulse of the jet is controlling the separation in efficient manner. The stream traces of velocity contour at different time intervals are shown below.

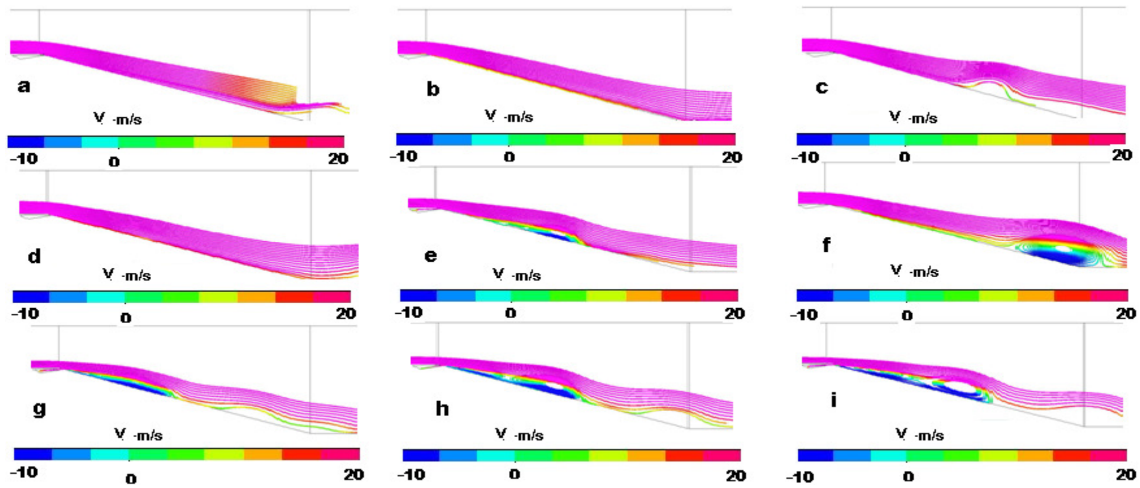



**FIGURE 18:** Velocity v-contour at pitch angle=30, VR=2and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The behavior of stream traces show that the pulse of the jet is effectively controlling the separation in the flow, there is a small separation observed at time interval of 0.03 sec shown by the fig [18(c)] but it is removed by the pulse of the valve. There is another separation zone in the flow very close to the valve, is moved further downstream to the ramp as shown by the fig [18(e) and (f)]. The pulse of the valve is controlling the separation by rotating vortex generation and separation area is reduced as shown by the fig [18(g)] ,but it is not removed completely from the flow as shown by the fig [18(h) and (I)].

The Micro Pulse Jet is controlling the separation well, while operating at above mentioned test parameters but not able to suppress the separation completely from the flow. The reason for that may be the valve is not able to produce enough energetic pulse of the jet which can remove the separation from the wall of the ramp. Overall results on the bases of controlling the flow separation and the quality of the flow are better than the results obtained from the pitch angle 45 degrees while operating at the same parameters. The velocity contours of the flow at various time intervals are shown below.

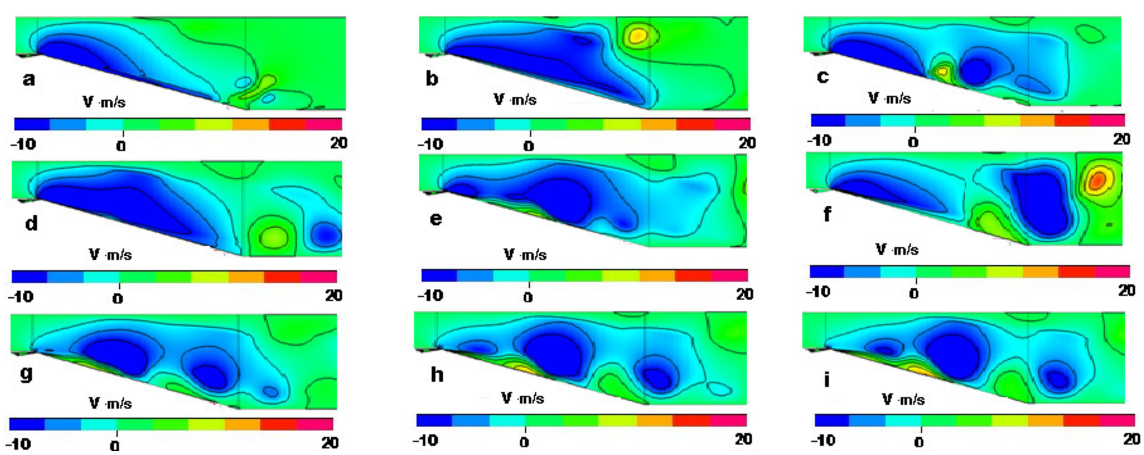
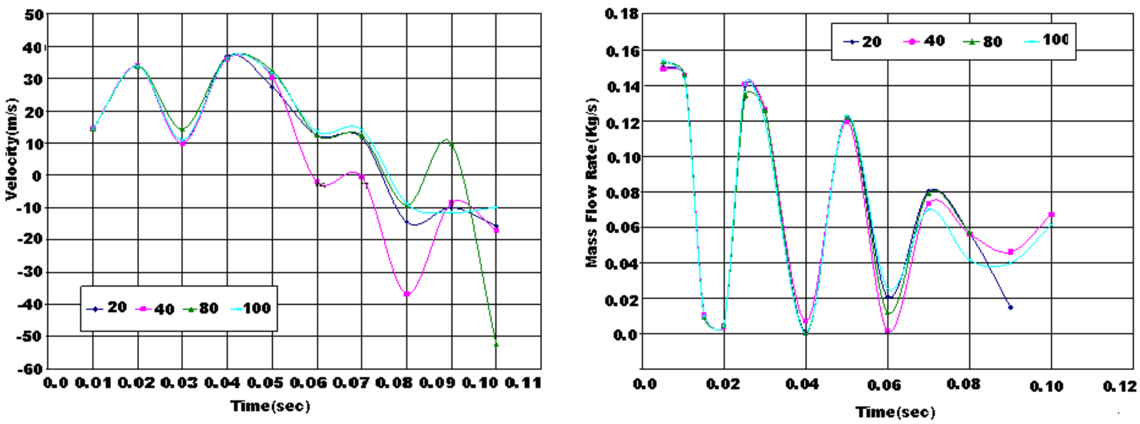



**FIGURE 19:** Velocity v traces at pitch angle=30, VR=2and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The trend of the velocity (v) contour shows that how effectively the separation is controlled by the pulse of the jet while operating at test parameter (B). Initially there is no significant separation observed in the flow except at 0.03 sec as shown by the fig [19(c)] but removed by the pulse of the jet as shown by the fig [19(d)]. It was investigated in all the test cases that due to the pulse of the jet there is separation just beneath the jet but the pulse of the jet is quite capable in removing and controlling the flow separation, as was observed in the case of test configuration (B).

A point is placed at 72 % downstream of the ramp in order to investigate the flow quality and magnitude of the velocity in more detail. The trend of the velocity magnitude is shown below,




(a)
(b) (b)

**FIGURE 20:** Plots at (VR=2, α=30) (a) Velocity plots at 72 % ramp length, (b) Mass flow rate requirement at various frequencies of 20, 40, 80,100 HZ

The trend line of the velocity plots show that the separation is controlled at the downstream of the ramp most of the time but at the end the separation is not removed by the pulse of the jet completely as shown by the fig [20(a)] and the magnitude of the velocity becomes negative which shows the existence of the separation. The separation is controlled though not removed completely but the results are better than the valve operating at pitch angle of 45 degrees with the same test parameters.

The mass flow rate requirement for suppressing the flow separation in case of pulse jet is significantly reduced from the steady jet. The mass flow rate requirement while operating at pitch angle of 30 degrees is appreciably reduces from the valve operating at 45 degrees, shown in the fig [20(b)].

**b) Results (VR=3, α=30 $^{O}$)**

This section of the document describes either the pulse of the jet at pitching angle 30 degrees, velocity ratio 3 with unsteady frequency of 80 HZ is capable of controlling and removing the separation in flow or not. A detailed study has been done to investigate the control action taken by the pulse of the jet, presented below,

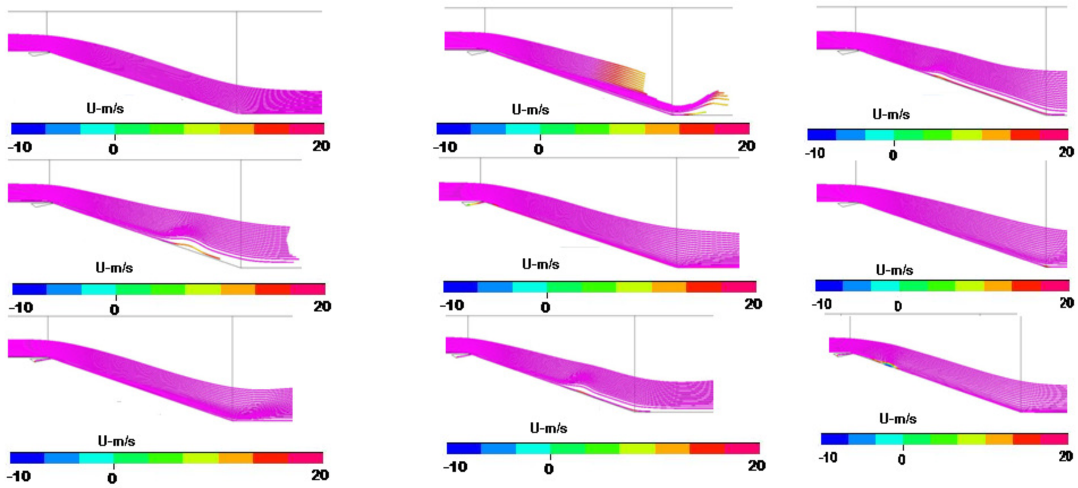



**FIGURE 21:** Velocity u-contour at pitch angle=30, VR=3and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The result for the Micro pulse jet at pitch angle 30 degrees shows the effective separation control. The valve while operating with this combination of condition is effectively in not only controlling the separation but also removing it completely from the flow. Under this optimum conditions there is no separation observed except at 0.03 sec which was a very thin portion as shown in fig [21(c)]. The pulse of the jet is quite energetic that it didn't allow the separation to grow and remove it completely from the flow as shown by the fig [21(g) to (I)].

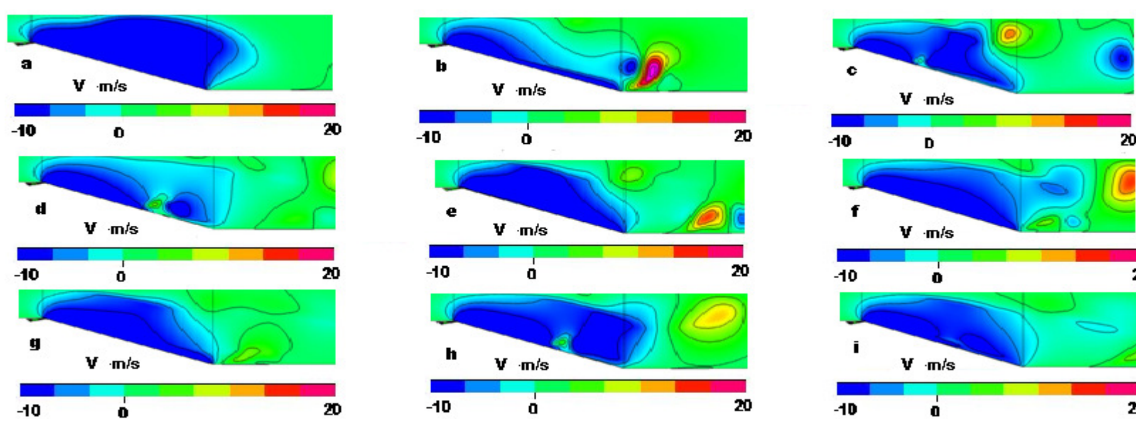
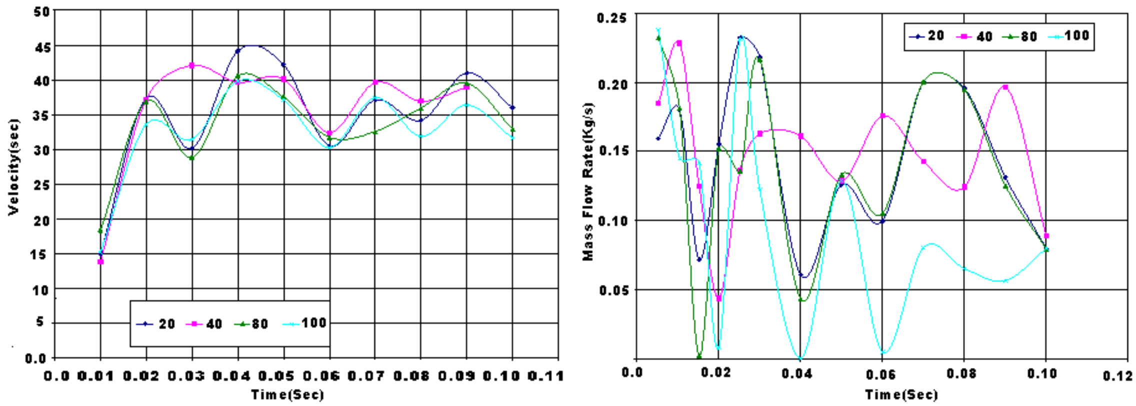



**FIGURE 22:** Velocity **v** traces at pitch angle=30, VR=3and 80HZ (a) Time=0.01 sec, (b) Time=0.02 sec, (c) Time=0.03 sec, (d), Time=0.04 sec (e) Time=0.05 sec, (f) Time=0.06 sec, (g) Time=0.07 sec, (h) Time=0.08sec (I) Time=0.1sec

The trend of velocity contour shows the effect of micro pulse Jet in separation control by the pulse of the jet operating at above mentioned parameters. The valve is operating with an optimum set of test condition in order to reduce and remove the separation completely from the flow as shown by the fig [22].




(a) (b)

**FIGURE 23:** Plots at (VR=3, α=30) (a) Velocity plots at 72 % ramp length, (b) Mass flow rate requirement at various frequencies of 20, 40, 80,100 HZ

The velocity plots indicate an ideal and optimum condition of the test parameters for the Micro Pulse Jet to control the flow separation effectively. The velocity at the 72 % downstream length of the ramp is shown by the fig [23(a)] and indicates that the velocity magnitude is positive throughout, reflects there is no existence of the separation in the flow. These results also show that the micro jet valve is operating at velocity ratio 3 with pitch angle 30 degrees at any frequency of the pulse is controlling the flow separation very effectively as compare to all the previous numerical results analyzed for the valve at pitch angle 45 degrees.

Same observation is found in all the test cases that mass flow rate requirement for controlling the flow separation in micro pulse jet is significantly reduce as compare to the steady jet case. The mass flow rate is reduce as compare to the same case at pitch angle of 45 degrees but higher than the valve operating at velocity ratio of 2 with same pitch angle. The trend of mass flow rate is shown in fig [23(b)].

## 8. SUMMARY OF RESEARCH WORK

A comprehensive numerical study has been done to show the effectiveness of the conceptual modeling of Micro Pulse Jet to control the flow separation. The Micro Pulse jet valve is modeled through periodic Inlet boundary condition with the help of mathematical function. The basic purpose of the valve is to suppress the separation by creating the rotating vortex which enhances the mixing between the energetic free stream flows with the separated boundary layer flow through the pulse of the jet. The results presented in the paper clearly indicate the Micro pulse jet is capable of reducing the flow separation in a severe separated flow.

The other finding of this paper is that the conceptual model of Micro Pulse Jet can generate the jet up to Mach 0.5 with only 20 % pressure ratio i.e. the total pressure is more than the atmospheric pressure.

In order to validate the effective control of separation by Micro Pulse Jet a 2-D ramp with 20 degrees of divergence is selected. The lower wall of the ramp is diverged enough to create the adverse pressure gradient and hence having a severe separated permanent region in the flow. The unsteady frequency of the flow is estimated by introducing various points in the separated region and then from the unsteady behavior the frequency of unsteadiness is calculated. A jet of 2 mm width is introduced at the upstream of divergent portion and flow is suppressed completely by the pulse of the jet as shown in the results. The jet amplitude is varied by the pressure ratio which ultimately controlling the velocity ratio (Vj/ V∞), ranging from 0 to 5 and the unsteady frequency is changed from 0 to 100 HZ.

**The Optimum Condition for the Control of Flow Separation Through Micro Pulse Jet** is estimated by analyzing four different test configurations. These configurations can easily be classified into two groups according to the Pitch angle i.e.45 and 30 degrees and then further classified each group in two sub groups according to the velocity ratio i.e. 2 and 3.

The results can be summarized as fallows

- The velocity contour plot suggests that the flow quality and the separation for the valve operating at velocity ratio of 3 with pitching angle of 45 degrees at 80 HZ is better than the valve operating at velocity ratio 3 with pitching angle of 30 degrees at 80 HZ.
- The stream traces plots indicate that the flow separation is reduce when the valve is functioning at velocity ratio 3 with pitching angle of 45 degrees as compare to the flow at pitch angle of 30 degrees with velocity ratio of 2, but the separation is not removed completely. For a qualitative analysis the valve is reducing 50 % more separation as compare to the condition at velocity ratio 2.3 and pitching angle of 45 degrees at 80 HZ.
- The data of the velocity for the certain points in the computational domain suggest that the flow control by the valve at pitch angle of 45 degrees is better than the valve operating at velocity ratio 2 and pitching angle value of 30 degrees. Though the velocity plot for velocity ratio of 3 has the positive value throughout the simulation as compare to the velocity ratio 2 clearly suggest a good control on separation but still there is some separation as the value of velocity ratio 3 is touching almost zero velocity line as shown by the following figure [24].

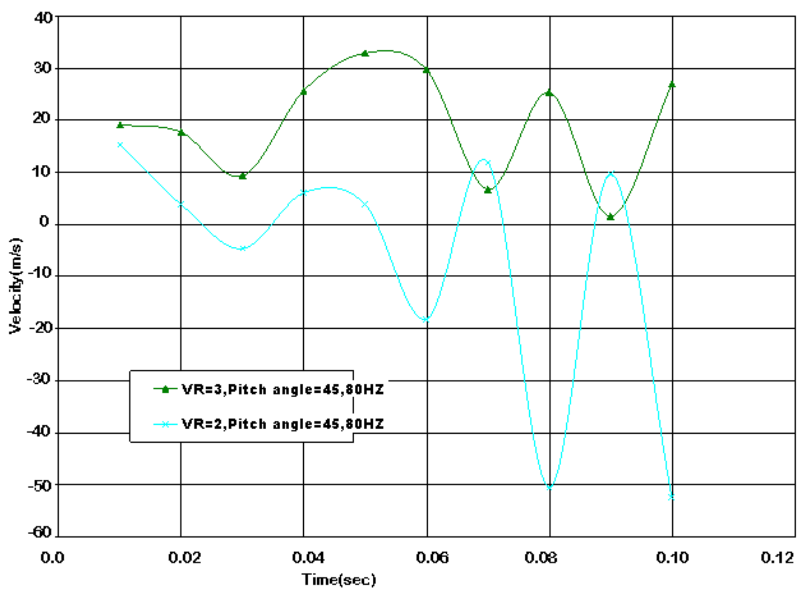



**FIGURE 24:** Comparison of velocity plots at different test configuration (A)

- The mass flow rate requirement for controlling the flow separation is almost 50% less than the valve while operating at velocity ratio of 2 and pitching angle 45 degrees at 80 HZ but the mass flow requirement of unsteady jet is significantly reduce than the steady jet as shown in following figure[25].

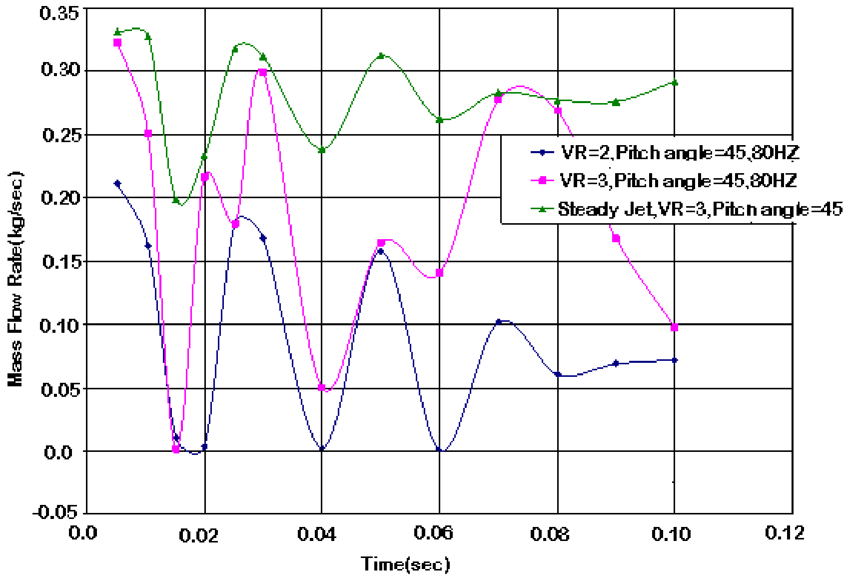



**FIGURE 25:** Comparison of Mass flow rate at test configuration (A)

- The velocity contour indicates better results of the valve operating at pitch angle 30 degrees, velocity ratio 3 at unsteady frequency of 80 HZ than the valve operating at velocity ratio of 2.
- Flow visualization for the stream traces indicate better results of the flow in controlling the flow separation for the pulse of the valve while operating at a=30, VR=3 and frequency of 80 HZ as compare to the valve operating at velocity ratio 2. For the qualitative analysis it reduces the flow separation almost 100 % as compare to the case with velocity ratio of 2.
- The velocity data of the point in the computational domain suggests that there is no separation zone for the test parameters of the valve operating at 30 degrees of pitch angle, velocity ration 3 and unsteady frequency 80HZ because the velocity magnitude is positive as compare to the valve operating at velocity ratio 2 having negative velocity as shown in the fig [26].

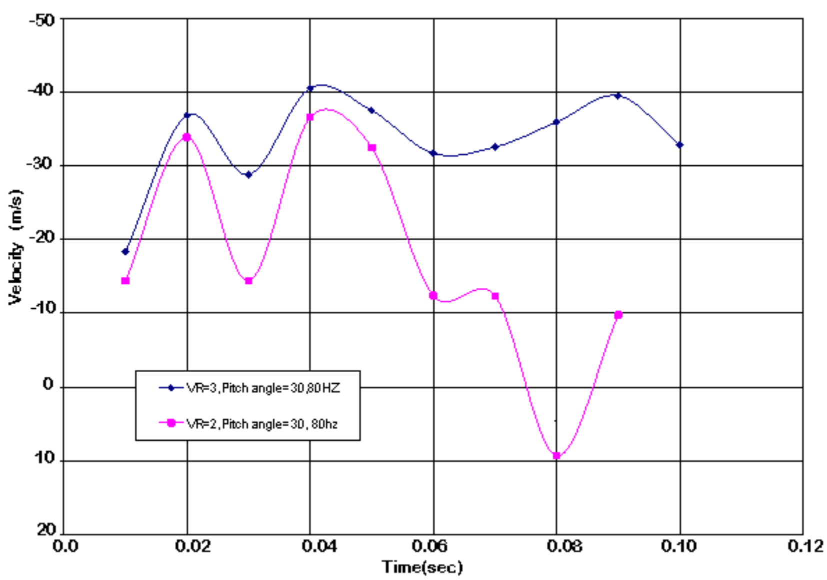



**FIGURE 26**: Velocity plots comparison for the test configuration (B)

- The mass flow rate requirement for the test case with pitch angle 30 degrees, velocity ratio 3 with pulsing frequency of 80 HZ is almost 50 % more than the valve operating at velocity ratio 2. The mass flow rate for the unsteady jet significantly reduced for the unsteady test cases as shown in the fig [27].

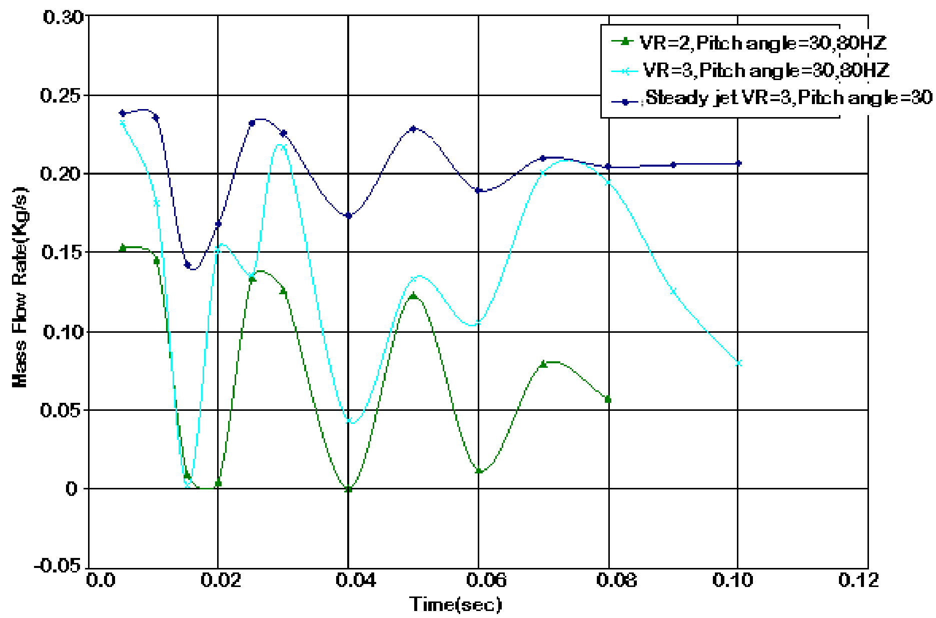



**FIGURE 27**: Comparison of Mass flow rate at test configuration (B)

From the flow visualization and comprehensive numerical analysis suggest that the flow separation is completely removed by the valve with the optimum test parameters setting of velocity ratio 3, pitch angle of 30 degrees with the unsteady frequency equal to 80 HZ. This optimum frequency is almost double from the calculated unsteady frequency for the base line case.

So on the bases of the results it is quite clear that the Micro Pulse Jet is completely feasible. Due to the compact size of the valve and less power requirement, it can be easily accommodated in any system for controlling the flow separation either in an external Aerodynamic application e.g. in aircraft wing, MAU'S wing or in canard or high lifting device or in an internal flow like in turbo machinery etc.

## 9. CONCLUSION

The basic aim of this paper is to describe the new conceptual approach of controlling the flow separation by Micro Pulse Jet. The effectiveness of this new method is validated by the numerical modeling of the valve by periodic Inlet boundary condition. The key finding of this research work describe as fallows

- Practical designing of Micro Pulse Jet is completely feasible.
- In order to control the flow separation, various combinations of test configuration were analyzed and it was found for effective control of flow separation the velocity ratio, Pitch angle and the pulse frequency play an important role.
- It was investigated in all the test cases that the mass flow rate requirement for controlling the flow separation is reduced significantly for the unsteady jet as compare to steady jet.
- The optimum condition for Micro pulse Jet operating at pitch angle 45 degrees must have velocity ratio 3 with unsteady frequency of 80 HZ

- It can be concluded from the analysis that when the unsteady jet is operating at pitch angle 30 degrees, it should have velocity ratio 3 and unsteady frequency of 80 HZ.
- The overall optimum set of test parameters for the valve in controlling the flow separation completely, should operate at the velocity ratio3, pitch angle 30 degree and pulse frequency of 80 HZ.
- The optimum pulse frequency is almost 2 times from the unsteady frequency which was calculated in base line reference case.

The overall efficiency of Micro pulse Jet can be easily compared with the other methods for controlling the flow separation in the following manner

- The working principal of Micro Pulse Jet is very simple and comparable with the other active flow techniques in the form of Pulsed Jet actuator in which there must be an external source for producing the pressure gradient across the valve instead of using the existing pressure difference as in case of Micro pulse Jet.
- As there is no external source is required in Micro Pulse Jet for creating the pressure difference which reduces the complexity of the system and having low value of the parasite drag as compared with the other active flow control techniques.
- The efficiency of the valve is higher as compare to other passive flow control methods like in VGS and Micro VGS due to the timely action of control for suppressing the separation in the flow.
- The jet of higher velocity can easily achievable in compact and small configuration of the Micro Pulse Jet valve as compare to zero net mass flow technique (SJA) and tangential blowing and suction method.

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