ANALYSIS OF MULTI ROW DISK INLET DEVICE IN SUPERSONIC FLOW CONDITION

Jayanta Sinha[1], Dr. Konark Arora[2], Dr. Om Prakash[3], Swarnadeep Bandopadhya[4], Paulam Partha Pratim Saha[5], Arnab Bhattacharya[6]

[1, 2, 4, 5, 6] *Amity Institute of Aerospace Engineering, Amity University, Sector-125, Noida, Uttar Pradesh*

[3] *Department of Aerospace Engineering, UPES Dehradun*

[1] *jsinha1@amity.edu*, [2] *karora3@amity.edu*, [4] *arnabbhattacharya6@gmail.com*, [5] *paulam.saha1997@gmail.com*, [6] *swarn1997@gmail.com*

ABSTRACT

This paper presents the CFD validation, simulations and subsequent analyses carried out on Multi Row Disk (MRD) inlet devices at Mach 2 and 3. This is a modernistic supersonic air inlet utilizing disks to create cavity-type surfaces on the frontal conical nose of the device. One of the existing models proposed by Japanese Aerospace Exploration Agency (JAXA) was modified and the changes in acoustic behavior, pressure fluctuations and drag coefficient were monitored. In addition, a MRD device has been designed using a different value of semi-cone angle and Length-to-Depth ratio. It has reduced the operational noise and the drag as compared to the conventional supersonic inlets.

Keywords: Multi Row Disk Inlet, Sound Pressure Level, Length to Depth ratio (l/d), Supersonic Inlet, Rossiter mode, Cavity flow, Acoustic signature, Drag coefficient (Cd)

Introduction

The nature of supersonic flow makes the inlet difficult to design and integrate into the airframe. In supersonic flight, the flow is decelerated by shock waves which can produce a total pressure loss in addition to the boundary layer losses [1]. The inlet serves a basic function of bringing the air required by the engine from free stream to the conditions required at the entrance of the fan or compressor with minimum pressure loss as in the case of turbojet engines. The absence of fans and compressor in ramjets and scramjets makes the role of inlets more important. The task of compressing the incoming air to conditions suitable for combustion has to be performed by the inlets. The compression is achieved by using single or a series of shock waves across which the flow properties changes discontinuously [2]. Thus, the Inlets used on supersonic and hypersonic aircraft present the ultimate design challenge for aerospace engineers. The ramjet inlet brings down the high-speed atmospheric flow down to subsonic conditions just before it enters the combustion chamber, by virtue of its inlet design. Stagnation temperatures of high value are present in this speed regime and variable geometry may not be a viable option for the inlet designer because of a possibility of flow leakage through the hinges.

Considering the above stated shortcomings, Kobayashi et al. proposed an innovative concept of a supersonic inlet in 2002-03, termed as Multi Row Disk (MRD) Inlet Device [3]. This inlet possesses a conventional conical-shaped centre body complimented by disk(s) arranged in the axial direction, as shown in Fig 1. This supersonic inlet design boasts of several advantages, namely, decrease in Cd, noise reduction, increase in total pressure recovery and better mass capture ratio. In addition, this inlet encompasses a simple design, which is desirable from the prospects of manufacturing and operation.

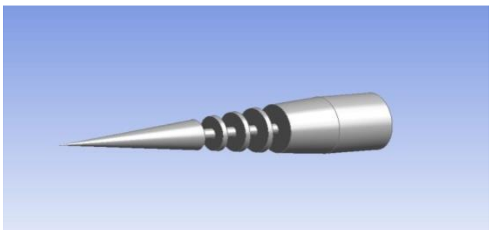

Fig 1: Multi Row Disk Inlet Device

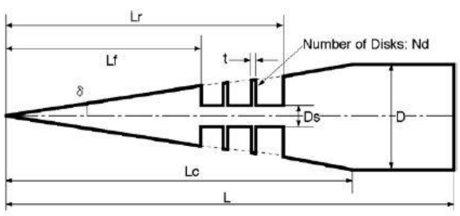

Fig 2: Schematic diagram of MRD [2]

The flow inside the cavity, formed by the disks, generally is of highly unsteady nature and comprises of complex flow fields including shear layer instabilities, several vortices, flow separation & re-attachment and shock waves [4]. There are several literature available on the fundamentals of cavity flow whether rectangular or axisymmetric [5-10]. Cavities are generally classified into open cavites (L/D<10), Transitional cavity (10<L/D<12) and Closed cavity (L/D>12). Open cavities have shear layer bridging the length of the cavity and the closed cavities have shear layer impinging and exiting from the base of the cavity. Several active and passive control techniques have been adopted by researchers to suppress the adverse effects of complex flow inside the cavity. Some of the Passive techniques used such as front wall inclination [11], passive external bleed [12], passive venting system [13] etc. Some of the active techniques involve leading edge microjet injection [14], Piezoelectric bimorph actuator [15] etc.
Since cavity flow is highly unsteady [7], mesh convergence study was to be carried out. Acoustic analysis is of paramount importance. In agreement with the 'Rossiter mode' of cavity flow [16], the 'Kelvin-Helmholtz instability' causes the shear layer to develop into vortices. A large re-circulation zone is established within the cavity walls as the flow proceeds further downstream and detaches itself from the leading edge of the cavity. The collision of fluid flow with the trailing edge set the stage for generation of pressure pulses (acoustic waves). Re-circulation of air establishes a feedback system wherein the flow impinges at the cavity's leading edge, bringing about the formation of compression waves. Aero-acoustics also induces structural vibration and causes fatigue in the MRD inlet structure [17].
Further researches carried out in this domain presented the variation of drag coefficient with angle of attack [4]. Kobyashi et al. observed that in addition to the above advantages provided by the cavity model, there was an inherent disadvantage associated with it. Presence of a single cavity increased the drag. But their study was limited to models without disk having only one cavity. To counter this effect of increased drag we have proposed to increase the number of cavities by inserting a disk inside the cavity, thus altering the l/d ratio. In subsequent section of the paper the performance of newly designed MRD device has been discussed in terms of its acoustic signature, wetted pressure distribution and the drag. Two cases have been reported and compared in this paper. In first case we have modified the existing type 3 MRD device as reported by Kobyashi and in the second case we have developed our own MRD device with varying cone angle and l/d ratio.

Computational Set-Up and Design Modifications

Computational work has been carried out using commercial software Fluent. Figure 3 shows the proposed modification on the single disk MRD device. First modification was done on the exisiting type 3 model reported by kobyashi [4], given in column 4 of the table 1. The 2nd modification was done by altering most of the geometrical parameters of the MRD device, which is reported in column 5 of table 1.

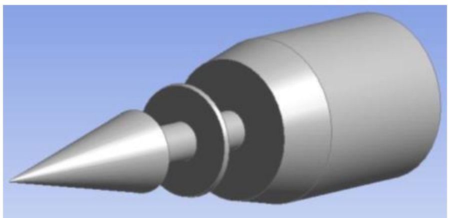

Fig 3: Isometric view of Self-designed MRD

Grid independence studies were carried out using the data reported by Kobayashi et. al. [4]. They reported the drag coefficient data for different types of the experimental models (types-1, 2 and 3), whose dimensions are listed in Table 4. Different grid configurations with varied wall y+ and grid fineness were tested. Fine and medium 2-D meshes with 550000 cells and 285000 cells respectively, were generated using ICEM CFD meshing tool. Table 1 provides the comparison of the experimental and numerical data for the fine mesh and table 2 provides the comparison of the drag coefficient for the coarse and fine meshes. Error has been reported for each case.

Grid Validation (Mesh Convergence)

FINE MESH	TYPE 1	TYPE 2	TYPE 3
REFERENCE DATA [2]	0.076	0.08764	0.1035
SIMULATION DATA	0.07854	0.0838	0.1021
ERROR%	3.342105	4.38156	1.35266

Table 1: Fine Mesh results

COARSE MESH	TYPE 1	TYPE 2	TYPE 3
REFERENCE DATA [2]	0.076	0.08764	0.1035
SIMULATION DATA	0.07878	0.0863	0.10259
ERROR %	3.65789	1.52898	0.87923

Table 2: Coarse Mesh results

Model Type	FINE MESH	COARSE MESH	Difference (%)
TYPE 1	0.07854	0.07878	0.305576776
TYPE 2	0.0838	0.0863	2.983293556
TYPE 3	0.1021	0.10259	0.479921645

Table 3: Grid Independency Test

	Type 1	Type 2	Type 3	Type 3 (Modified)	Self-designed MRD
D(mm)	40	40	40	40	30
δ (degree)	8	8	8	8	12
L (mm)	182.3	182.3	182.3	182.3	100
L_c	142.3	142.3	142.3	142.3	70.5
Length (l) and depth(d) of the cavity				13.05mm and 8.7mm respectively. (variable due to inclinations)	12mm and 4mm respectively. (variable due to inclinations)
Ds (mm)	-	7.3	8.6	8.6	7
Td (mm)	N/A	N/A	N/A	2	1
Nd	N/A	N/A	N/A	1	1
No of cavities	1	1	1	2	2

Table 4: Dimensions of the computed models [2]

Effects of different disk geometries

The dimensions of the validated models have been extracted from the experimental work done by Kobayashi et al. [4]. Type-3 (Modified) model has been constructed by inserting a 2mm disk exactly at the mid-section of the cavity, whereas the designed MRD (discussed in the later sections) has a 1mm disk at the center of its cavity. The following parameters that have been observed and analyzed for the performance of the MRD are:

- Drag Coefficient
- Acoustic behavior
- SPL
- Pressure variation along the cavity walls

Results and Discussions

- **TYPE 3 MRD MODEL (MODIFIED)**

After the application of 2 mm disk inside the cavity, the l/d reduced to **1.48** (appx.) & reduction of Cd was observed as tabulated in Table 5:

MRD model	Reference Data (No disk) [2]	Simulated Data (With Disk)	Reduction (%)
Type 3	0.1035	0.0945	8.69

Table 5: Change in coefficient of drag (Cd)

The addition of a disk has subjected the MRD inlet device to form two cavity structures of reduced l/d ratio, providing reduced mean values of pressure, especially at the rear wall as compared to the one without disk, as reported by Kobyashi et al.[4]. Vortex structures inside the two cavities and the mean pressure distribution over the walls of the 2nd cavities can be seen in the figure 4 and 5 respectively. Non-dimensionalised peak pressure, P/P_o plotted over the wetted length of the 2nd cavity i.e. the cavity after the disk shows that highest peak pressure on the front and base wall could be around 0.20, whereas it rises to 0.75 for the rear wall. The pressure fluctuations at the rear wall are of the utmost significance since this region solely governs the generation of acoustic waves, as explained by Rossiter [16].

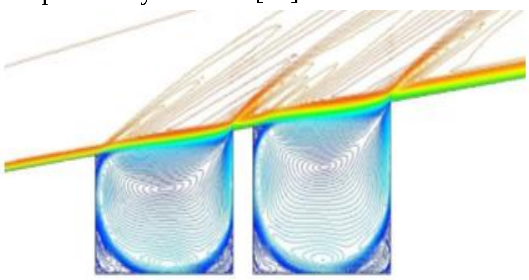

Fig. 4: Mach contour at modified MRD Type-3

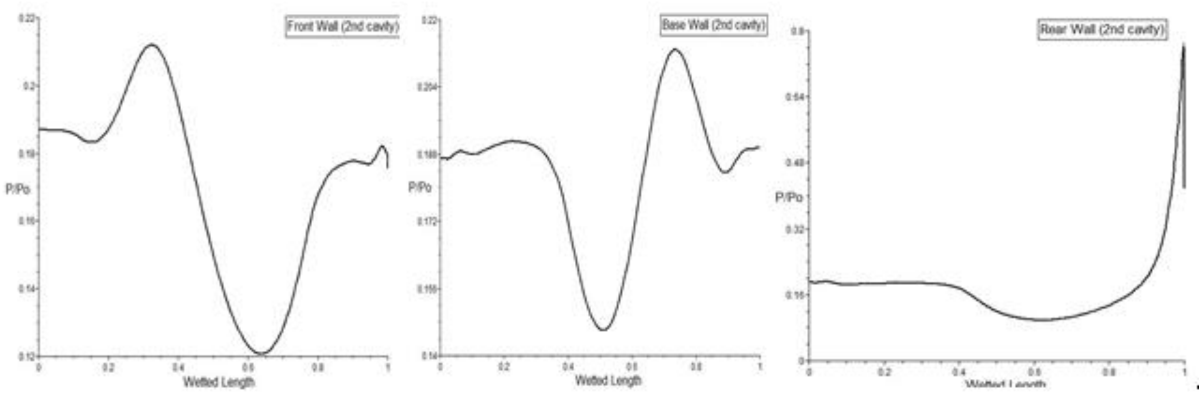

Fig. 5: Pressure variation along the front (a), base (b) and rear (c) walls of the 2nd cavity (Type-3 modified MRD)

Acoustic data has been monitored at the rear wall top corner of the 1st cavity (Point 1) and the front wall top corner of the 2nd cavity (Point 4). The SPL level clearly indicates that for the cases the dominant frequency is around 38 KHz and it also outline the effects of inserting the disk in the level of acoustic magnitude. The overall sound pressure level (OSPL) measured at the rear wall of the first cavity is 191.395 dB, but this level rises to 192.75 dB at the rear wall of the second cavity, on employing the disk. Therefore, it can be concluded that the use of disk in type-3 increases the operational noise, which is one drawback of this model. Figure 6 gives the detailed SPL plot at point 1 and 4.

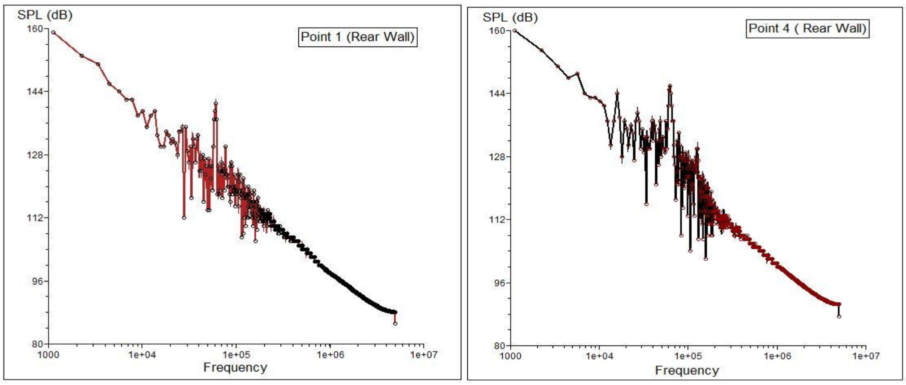

Fig. 6: SPL measured at point 1(left) and point 4 (right)

- **SELF-DESIGNED MRD**

This section discusses a MRD inlet device whose dimensions have been set based on the wind tunnel conditions and other design optimizations, as mentioned in Table 4. The flow conditions for the simulations have been summarized in Table 6:

CHAMBER PRESSURE	39408.56 Pa
TEMPERATURE	166.67 K
FLOW MACH NUMBER	2

Table 6: Boundary conditions for the analysis

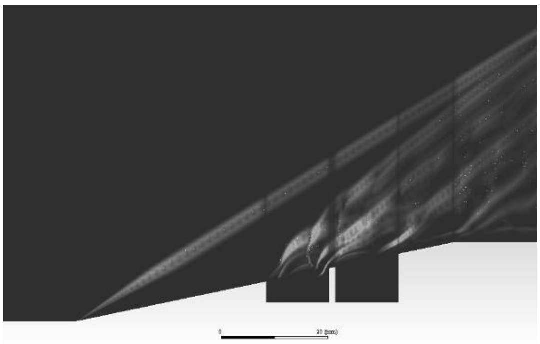

Fig 7: Density contour

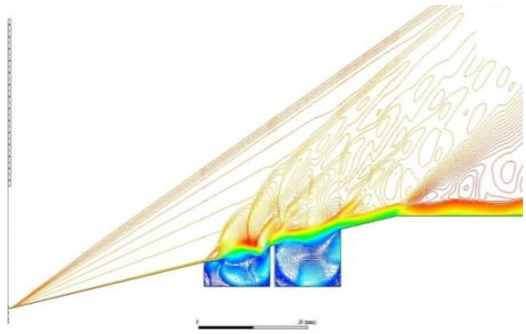

Fig 8: Mach contour

Fig 7 and 8 gives the shock structure around the MRD device. Cavities formed by the disk have a single vortex structure. High vortex shedding adds to the disturbance in the shear layer (Fig 8). Series of weak shocks ensure efficient compression as compared to a single strong shock at inlet. Figure 9 gives the pressure distribution of P/P_o drawn over the wetted length of the cavity for the entire front wall, base and rear wall of the 2nd cavity. The pressure distribution shows that even though the mean pressure over the front wall and the base marginally increases, the pressure level on the rear wall is pretty same as we got for previous modified MRD Type-3. Sound Pressure levels on the cavity walls, as shown in figure 10, have reduced as the flow proceeds aft of the disk, i.e. pressure levels aft of the disk are lower than that ahead of the disk. Therefore, it is safe to state that one or two disk used in MRD can produce large number of weak shocks that can improve the overall efficiency. OSPL level on the rear wall of the 1st cavity is 196.2 db and at the 2nd cavity rear wall is 183 db.

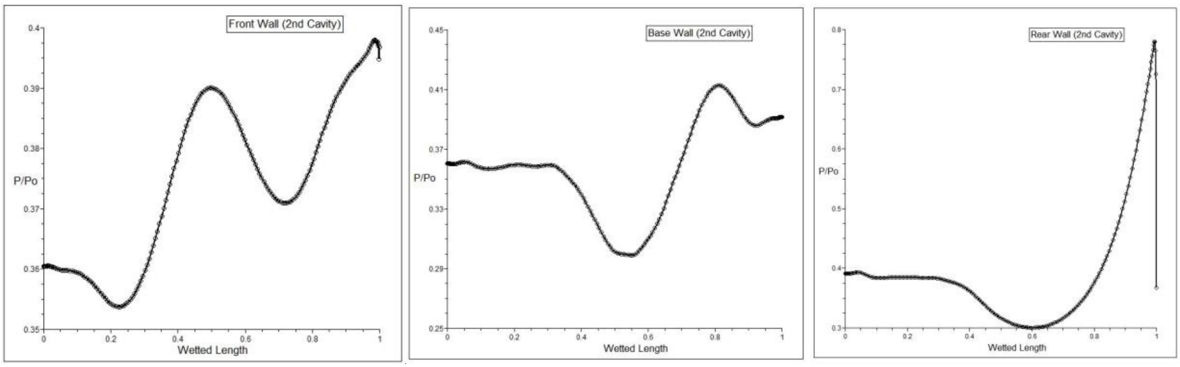

Fig. 9: Pressure variation along the front wall, base and rear walls (in order) of the 2nd cavity (Self-Designed MRD)

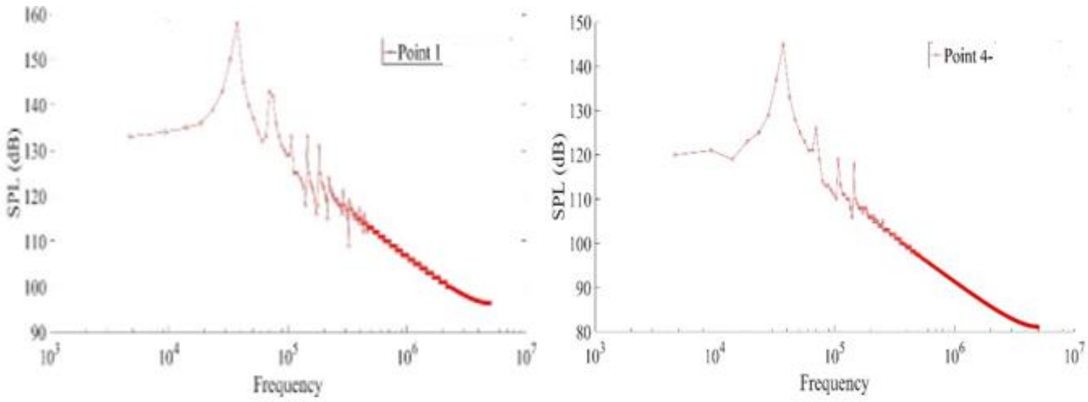

Fig. 10: SPL measured at point 1(left) and point 4 (right) for self-designed MRD

Conclusion

We modified an existing Type 3 MRD model by adding 1 disk and monitored the after-effects. With the insertion of a disk there is a decrease in the l/d ratio of the cavity, due to which there is a drop in the drag coefficient while the OSPL increased. The impingement pressure on the rear wall of the cavity is also reduced. So, the modification of type-3 MRD model couldn't provide the desired outcome in terms of cavity acoustics. So we designed a new MRD device and called it self-designed MRD model. Here the cavity l/d and cone angle increases and we observe a significant drop in the overall sound pressure level (OSPL). The cavity flow experiences severe pressure fluctuations owing to the formation of oblique shock waves, which has been reduced by inserting 1 disk. The flow characteristics could be improved by increasing the number of disks but it can causes high noise level. These kinds of vibrations might be mitigated by varying the cone angle, which is under investigation.

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