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Study of Aero-elastic Behaviour of an Aero Spike in Unsteady Supersonic Flow by FSI Simulation

A Kamalesh[1], P Theerthamalai[2], G Jagadeesh[3]

[1]Scientist, RCI, Hyderabad, India
[2] Technology Director, Directorate of Aerodynamics, DRDL, Hyderabad, India
[3] Professor, Department of Aerospace Engineering, IISc, Bengaluru, India
Corresponding author: kameshanand@gmail.com

Abstract: The structural behavior of a slender aero spike member on a flat faced cylinder model under supersonic unsteady flow conditions has been studied using Fluid-Structure interaction (FSI) simulations. The aero spike configuration has been selected by carrying out axisymmetric CFD simulations at select Mach (M) to have maximum flow unsteadiness. 2-way FSI simulation has been carried out using Ansys software considering aluminium alloy for aero spike structure. The structural response of the aero spike has been studied at M 3.0 and $\alpha = 0°$, 5° and 10°.

***Key Words**:* FSI, unsteady, aero spike, FEM, CFD, supersonic

1 Introduction

The use of aeropike has been known for its drag reduction characteristics for highly blunt bodies. Works on aerospike has been dated back from 1952 and few flight vehicles have already been used them for its advantages [1]. However, the unsteady phenomena associated with these aerospike may trigger the structural vibrations over these slender members, sometimes leading to structural failure. Numerical study has been carried out to predict the transient pressure and force signatures over the flat cylinder model. The effects of flow unsteadiness on the spiked aero configurations has been studied to understand the structural characteristics of the airframe due to associated heavy pulsation/oscillation of shock waves.

In this paper, transient axisymmetric CFD simulations have been carried out at M 2, 3 and 4 and α 0° for two aero spike shapes and two slenderness ratios. The Fluid structural interaction simulation using Ansys Mechanical and Ansys Fluent has been carried out in this study at M 3.0 and α 0°, 5° and 10°for the aero spike configuration having the maximum flow unsteadiness.

2 Literature Review

The works on aero spike have started since 1952 by Mair.W [1] in which he has studied the interaction between fore body shock and the boundary layer over the spike thereby reducing drag. Frequency of spike oscillations has been observed to be 6 kHz. D J Maull [2] in 1960 has experimentally studied the spike oscillation using a sewing needle on five nose shapes at M 6.8. He has identified that flow oscillations have been very prominent for $0.25 \leq L_s/D \leq 2.5$. G Jagadeesh et al [3] in 2003 has reported that over a blunt 120° apex angle cone model, shock oscillations are less violent for blunt spikes as compared to sharp spikes at M 5.75. In 2004 Daniel Feszty et al ([5] and [6]) have brought the clear definition of pulsation and oscillation modes of shock wave unsteadiness over flat cylinder models.

3 Validation of CFD Results

The CFD software (Ansys Fluent) has been validated for its transient predictions of flow unsteadiness for flat faced cylinder models with aero spike. The experimental results from reference [5] and [6] for a flat faced cylinder model with sharp conical aero spike, (L_s/D=1) as shown in Fig.1., has been used to validate the software at M 2.21 for pulsation mode of shock wave. The model for oscillating shock waves has highly slender spike (L_s/D=2) (as shown in Figure 2) and has been tested at M 6.0.

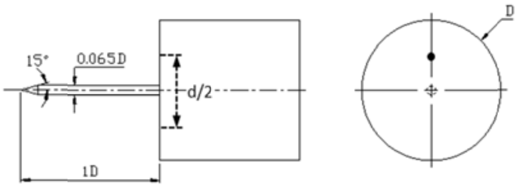

Figure 1 Model for pulsation

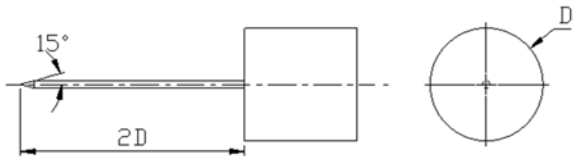

Figure 2. Model for oscillation

The transient numerical simulation has been carried out for flat cylinder model with sharp spike configurations to validate the commercial CFD software, Ansys Fluent. Both pulsation and oscillation phenomena have been simulated using k - ω (SST) model with a second order time accurate solver at time interval of 5ms for 2 second duration. The results were compared with those from [5] and [6] respectively. The velocity vector plots in Figure 3 shows the pulsation pattern of shock waves over the aerospike region at M 2.21 at different time sequences (1-12). Similarly the time sequenced sub-figures (1-12) of velocity vectors in Figure 4 explains the oscillation pattern of shock wave over flat cylinder model at M 6.0.

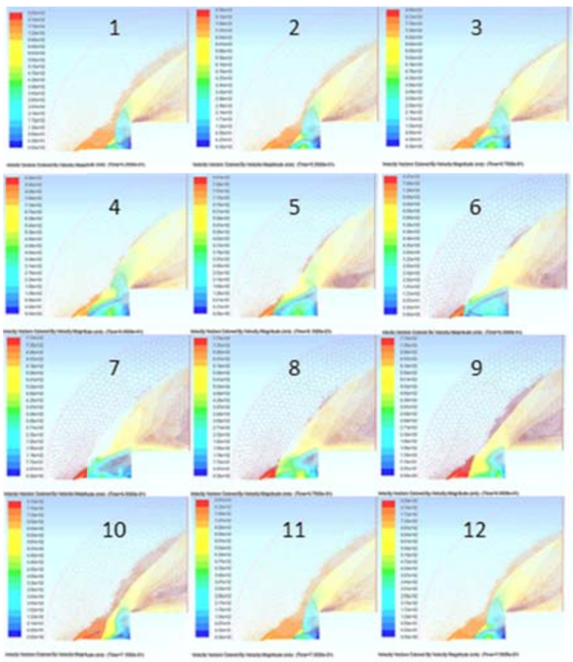

Figure 3. Pulsation, M 2.21, α 0°

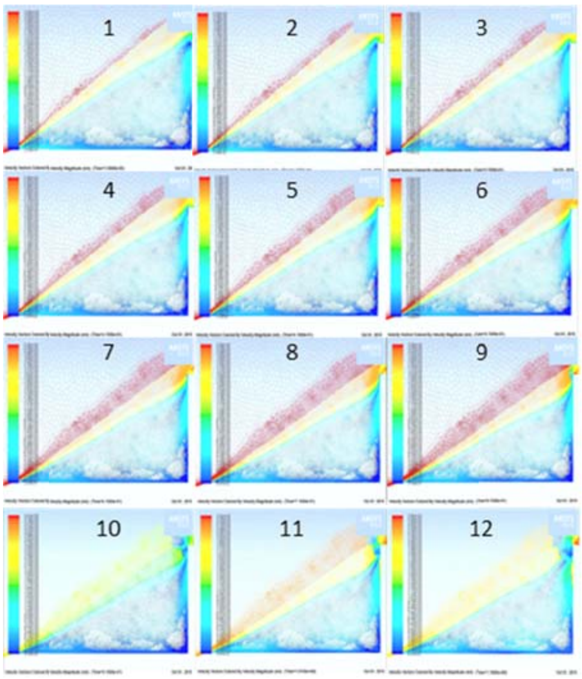

Figure 4. Oscillation, M 6.0, α 0°

The static pressure on the front facing face of model at a location d/2 (ref. Fig.1) has been compared with the experimental results of [5] and [6] for pulsation and oscillation flows and have been shown in Figure 5 and Figure 6 respectively. The non-dimensional experimental pressure values reported in the lliterature has been scaled appropriately and found to compare very well with the numerical data. Thus it can be derived that the CFD code can be believed for unsteady axisymmeteric flow analysis over aerospiked configurations atleast in the time scale.

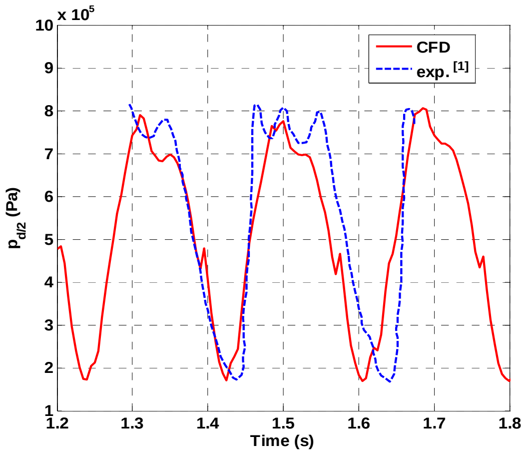

Figure 5. Pressure history - pulsation, M 2.21

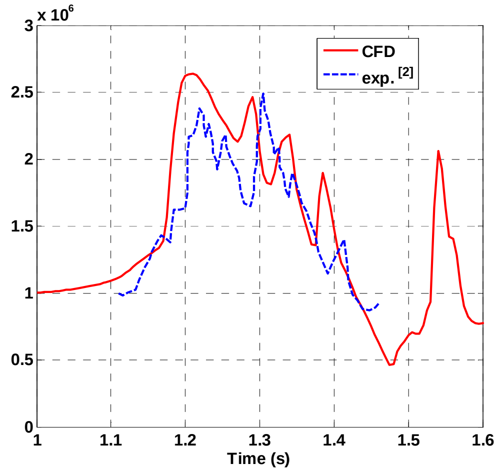

Figure 6. Pressure history - oscillation, M 2.21

4 Axisymmetric Transient CFD Analysis

A flat faced cylinder model with sharp and flat disc tipped aerospikes of L_s/D=0.75 (37.5mm) and 1.5 (75mm) (as shown below), have been considered for the present study.

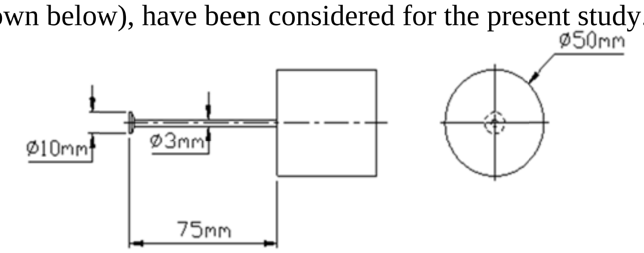

Figure 7. Flat cylinder model with flat disc spike

Axisymmetric numerical transient analysis has been carried out for these configurations using Ansys Fluent software. Best practices for CFD simulations have been followed, viz., grid independance study, parameter selection, convergence studies, etc. The pressure farfield boundary conditions have been set for M 2.0, 3.0 and 4.0 with operating pressures of 3, 5.5 and 6.5 bar respectively at a total temperature of 300K and α 0°. Density based solver with k-ω SST turbulence model has been used to capture the complex flow field near the spike-face region. The steady state solution has been solved for all the cases and initialised for the transient simulation with a time step of 10μs and 50 iterations for every time step. The results of all these simulations are discussed below.

a. Sharp spike – 0.75d: As shown in Fig.8. the static pressure probed at a distance d/2 location along the time history has shown high pulsations at all three M. The frequency of pulsations have been noted to be around 1.3 to 1.4 kHz for this configuration and the pressure contour plot for nine time sequences with time interval of 16μs has been shown in Fig.9.

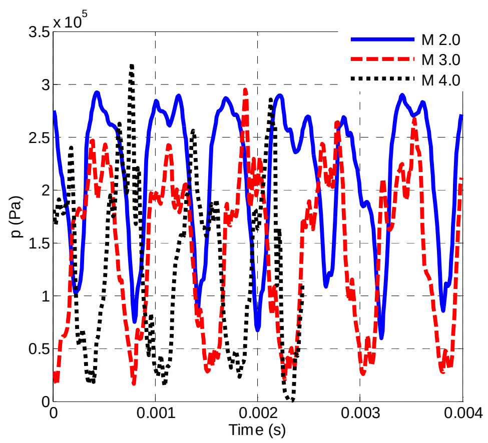

Figure 8. Sharp spike, 0.75 l/d

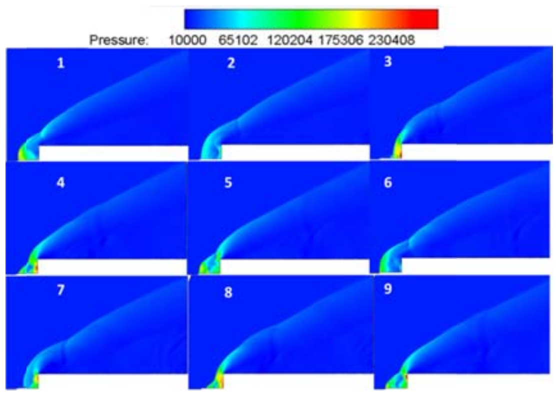

Figure 9. Pressure contours – Sharp spike (0.75D), M 3.0

b. Sharp spike – 1.5d: When the spike length has been increased from 0.75d to 1.5d, the unsteadiness seemed to have died down at M 2.0 but at M 3.0 and M 4.0 there were visible oscillations observed near the spike region. The frequency range have been found to be between 0.9 to 1.2kHz for these M and very low pressure jumps at d/2 location for M 2.0 as seen in Fig.10.

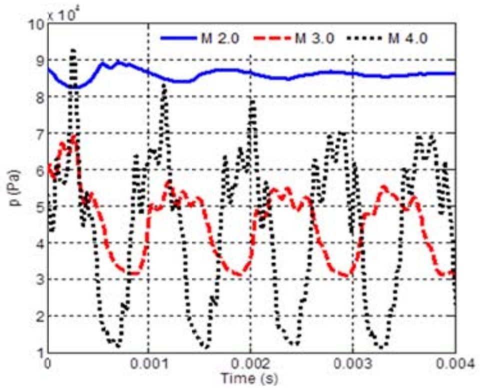

Figure 10. Sharp spike, 1.5 l/d

c.Flat disc spike – 0.75d: The flat disc spike has a very strong detached shock at spike tip than the sharp spike case. It can be seen from Fig.11 that the pulsating pressure values have been dominant at d/2 location at M 2 and almost steady at M 3 and M 4 cases. The frequency spectrum of unsteadiness at M 2.0 has been observed close to 2 kHz and though the pressure jumps are very low (~2%) and damping out, the frequency of pulsations have been found to be around 2.7 kHz.

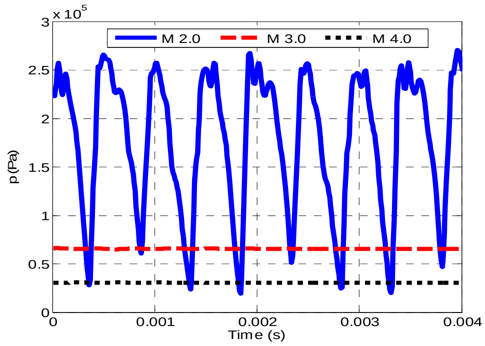

Figure 11. Flat disc spike, 0.75 l/d

d. Flat disc spike – 1.5d: The flow for this configuration has been very steady with very low pressure jumps (2% at M 3.0) which eventually damp out as seen in Fig.12.

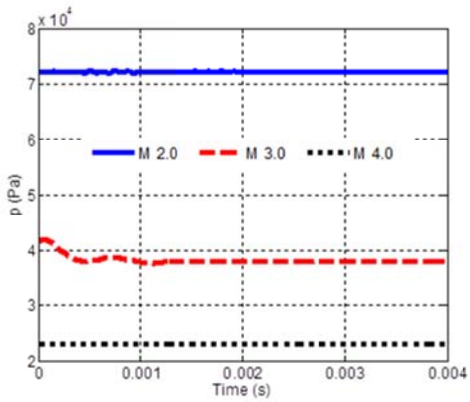

Figure 12. Flat disc spike, 1.5 l/d

From the above results it is inferred that the shape and the slenderness ratio of the aero spike tip plays vital role in the amplitude and frequency of the unsteady flow field. Sharp spike with 0.75d slender has been observed to have the highest unsteadiness and hence selected for FSI simulations.

5 Fluid Structure Interaction Simulation

The flat faced cylinder with 0.75D slender sharp aerospike has been modeled and meshed with very fine grid near the spike – flat face region to capture the unsteady flow field at M 3.0. Transient Stuctural and Fluid Flow model solvers are tigthly coupled in 2-way mode with Systems coupling module on the Ansys Workbench platform. The aero spike model has been meshed in Ansys Mechanical with its root end fixed and the external surface of the aero spike has been defined as the systems coupling surface. The elements of this aero spike surface has been mapped to the corresponding elements in Ansys Fluent for the transfer of displacement and forces between both the solvers during the Systems Coupling iterations. The FSI simultaions have been carried out at three angles of attack, viz., 0°, 5° and 10° in M 3.0 flow field with stagnation pressure and temperature of 5.5 bar and 300K respectively.

The aerospike structure has been modeled as aluminium alloy for the structural analysis. The FSI simulation has been run for 300 micro second for α 0° and 10° and 120 micro second for α 5° with a time interval of 1 micro second to record 2-3 cycles of von-Mises stress. The systems coupling iterations has been set to 10 for the 100% transfer of forces and displacements across Stuctural and Fluid solvers. A typical pressure contour at M 3.0, α 0° has been shown in Figure 13, which shows the aero spike shock wave interacting with the stronger shock from the shoulder of cylinder. This may be the cause of initiation for the unsteady shock pulsations due to mass flux trap and escape cycles in spike-face region.

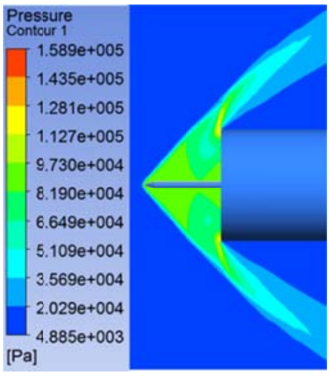

Figure 13: Pressure contour at M 3.0, α 0°

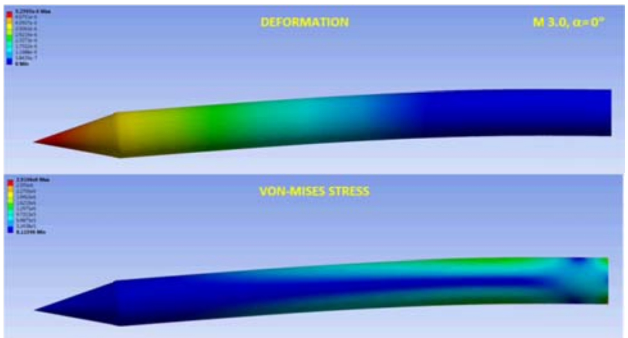

Figure 14: Deformation, stress contour at M 3.0, α 0°

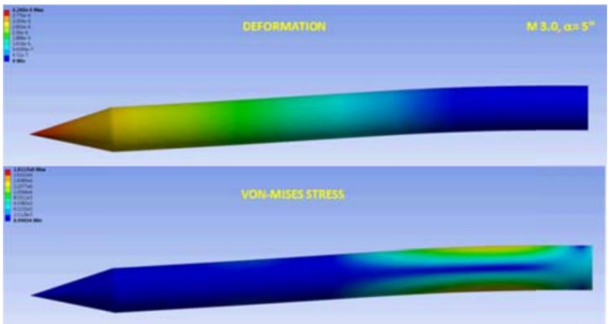

Figure 15: Deformation, stress contour at M 3.0, α 5°

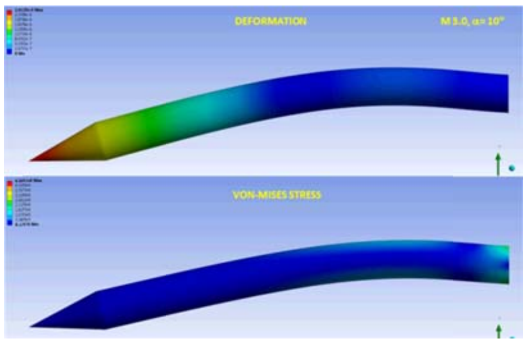

Figure 16: Deformation, stress contour at M 3.0, α 10°

Effect of α: The FSI simulations have been run at M 3.0 and α 0°, 5° and 10° and the results are analyzed here. The deformation and the corresponding von-Mises stress contours have been presented in Figures 14 to 16.

(i) ***α = 0°:*** With the flow axis aligned with the model longitudinal axis the shock wave pulsations are purely along this axis only. From Figure 14, 17 and 18, it can be seen that the lateral deformation of the aero spike is of the order of 4 μm and with a maximum bending stress of 3Mpa. The stress cycles have a frequency of 12kHz and the deformation has 7.7kHz for a shock pulsations of 1.4kHz. The order of deformations and stress are insignificant to cause any structural damage to aero spike or to cause inflamation of unsteady shock wave pulsations.

(ii) $\alpha = 5°$: The flow being inclined to model at 5 degree still the deformations are of the same order that of 0 degree. This suggests that the shock wave pulsations are along the model axis and not along the flow axis. However the amplitude of bending stress on the aero spike is lower than 0 degree case by half but with higher frequency (27 kHz) as shown in Figure15, 17 and 18.

(iii) $\alpha = 10°$: At 10 degree inclination, the spike deflections are reduced drastically (25% of 0 and 5 degree cases) but the bending stress has maximized compared to other cases. But still the order of stress is insignificant to cause any structural failures. The stress cycles has a frequency of 11kHz and the spike oscillation frequency of 22kHz as seen in Figures 16, 17 and 18.

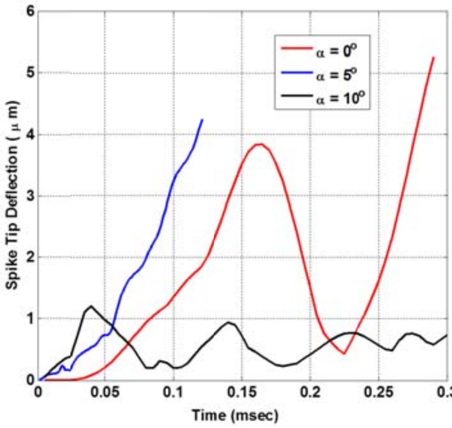

Figure 17: Absolute lateral tip deformation of spike

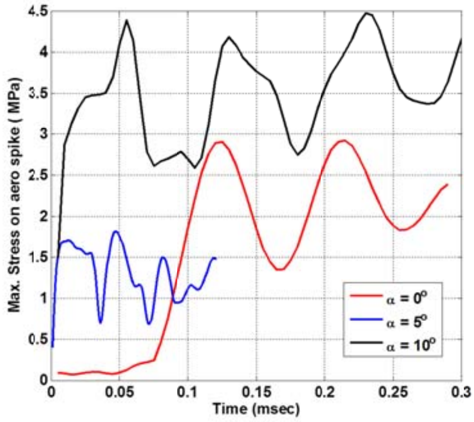

Figure 18: Maximum stress history of spike

6 Conclusion and Future Work

From the above results and analysis, it can be seen that for aluminium aero spike in unsteady supersonic flow is structurally safer at these study conditions. Even for a fatigue failure the stress amplitudes are far lower than the threshold limits and hence can withstand these loads for infinite number of stress cycles. However, if the magnitudes of stresses increase beyond the threshold fatigue stress limit at any other M, α or pressure combinations the aero spike member would fail after certain cycles. More detailed studies along with experiments have been planned in future to verify at which conditions the aero spike structural failure can occur.

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