Review of the Flow-field Analysis Over Cavities

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Abstract: ***In this paper review of basic oscillation types, their numerical modelling, simulation approaches, and acoustic features of flow over cavities has been provided. Cavities in the supersonic and subsonic flow range have wide utilization but their numerical modelling varies significantly depending on the aerodynamics, structural and fluid dynamics considerations. Comprehensive review of application and advantages of numerical schemes like RANS, LES, DES, DNS model has been provided in the paper. Various cavity types and their characteristic features has also been provided along with their pressure oscillation mechanism and suppression mechanism. Mechanism of Shear layer generation and feed back loop has also been discussed along with cavity noise suppression techniques. Some Active and Passive techniques of noise suppression are also provided in the last section of the paper.***

Keywords: **Cavity flow, Cavity feedback mechanism, supersonic cavity, acoustic pressure, passive control, active control.**

I. INTRODUCTION

Lots of researches have been undertaken to establish the cavity flow features. A challenging area for a cavity based researches is the prediction of the structure of the cavity flow and the level of the pressure oscillations. Aero-acoustics is also a domain where accurate flow field predictions are quintessential. Large numbers of experimental and computational work over the decades have been dedicated to establish various features of cavity flow-field for different Mach numbers. A simple cavity structure can generate highly unsteady and complicated flow-field. This cavity shaped structure can be present in many real world applications like energy industry, automobile industries, and aeronautical industries. Flow over cavity generates high aero-acoustic pressure oscillations and induces high decibel noise. For a open roof car, the induced noise can reach upto 130 decibel [1]. The basic structure of a cavity flow is given in figure 1. The basic characteristics of the cavity flow are the generation of an oscillating shear layer, further amplification of the stream unsettling influences, and the resulting transformation of these aggravations into acoustic waves at the rear wall of the cavity [2].

At incompressible stream administration, general component stays same however acoustic waves remain absent. Vortex structure moves past the downstream corner [3] creating an irrotational flow field which additionally cause the excitation of shear layer aggravations. At high supersonic speed, shear layer emanating from the leading wall of the cavity propagates towards the rear wall where it impinges to produce rear wall strong shocks [4].

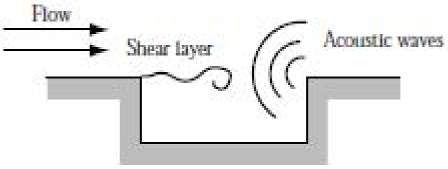

Fig. 1. Basic cavity model

Till date lot of researches on the basic cavity flow mechanism for different cavity oscillations have been undertaken, but the novel formulation of a quantitative model that could predict the amplitude and frequency of oscillations accurately is still a challenge.

The cavity problem also challenged the researchers to model the complicated flow pattern. Cattafesta et al.[5] extensively reviewed the control of cavity flow through disturbing the resonance mechanism and feedback loop. Rowley and Williams [6] also studied and highlighted the important developments in controlling cavity stream motions that were made in the previous couple of decades. Passive and Active control of cavity flow motions has likewise been recorded in the later segments.

II. CLASSIFICATION OF CAVITY

Cavities can be characterized in light of L/D proportion, L/W proportion, depression stream marvel and as indicated by the oscillation mechanism [7]. Whenever L/D proportion is more noteworthy than 13, it is called closed cavity, when L/D proportion is smaller than 10, it is called open cavity [8]. In open cavities, approaching free stream isolates at the cavity front wall and reattaches on the rear edge. Shear layer is shaped connecting the length of the cavity isolating the internal cavity stream and the free stream. The pressure difference between the internal cavity stream and free stream flow leads to the recirculation zone in a cavity. In the closed cavity, after the partition of free stream on the front wall, the flow attaches in a cavity at a point isolates from the cavity and re-joins at the stagnation point in the trailing edge [9, 10]. Schematic diagram of open and closed cavity configurations

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for supersonic flow is given in figure 2. Open cavities are always characterized by high level of pressure oscillations and smooth pressure over the wetted length of the cavity followed by a peak pressure at the rear wall. Closed cavities are characterized by rising static pressure distribution over the length of the cavity but acoustic level or pressure oscillations are considerably lower than open cavities.

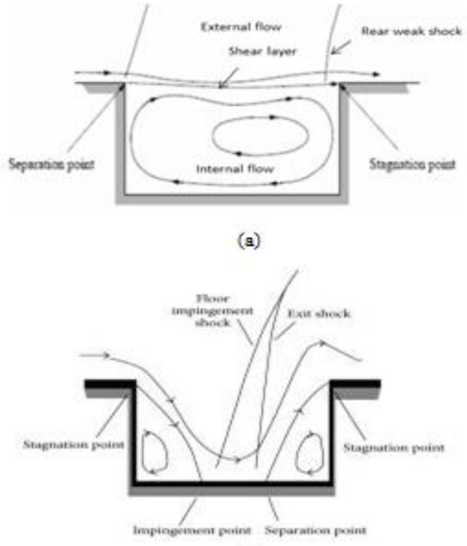


Fig. 2. Supersonic cavity flow over (a) Open cavity (b) Closed cavity.

III. CAVITY APPLICATION AND OSCILLATION ANALYSIS

During the 1960's, Rossiter [11] had done extensive research on flow over cavity flow at subsonic and transonic speeds where he gave detailed information on the flow physics of the cavity problem. He introduced the concept of formation of a feedback loop. Due to the loop there is a self sustained pressure oscillations. The aero-acoustic generated in the process has also become a research area for the scientists as it can compromise the stealth characteristics of modern day aircrafts The unsteady flow inside and near the cavity are susceptible to self-sustaining oscillations, occurs in a variety of applications such as slotted wall wind and water tunnels [11, 12] and slotted-flumes [13], bellows-type pipe geometries [14, 15], gate slots [16], aircraft components like Weapon Bays [17], Landing gear bays [18, 19], Scramjet flame holders etc. In weapon bays it was observed that the internal carriage of missiles can cause large level of pressure oscillations in the vicinity of the cavity, through which the missile has to pass through during launch. Problem in Scramjet combustion lies with the stability of the flame during the combustion process. The approaching supersonic stream stays in the combustor just for a brief time frame, of the order of milliseconds. Cavity wall injector is a new concept of an integrated fuel injection approach and flame holding. It provides stabilizing supersonic combustions and improves the performance, and combustion efficiency [21, 22]. K. M. Pandey et al. [23] have shown that two cavity based fuel injection techniques are used namely- Cavity flame holders and Cavity-Pylon flame holders. Cavity flame holder uses fuel injection upstream of the cavity and a backward facing step to give recirculation. This kind of cavity structure additionally gives a persistent ignition point or flame holder with least pressure drop and gives the lesser drag as separation of flow is little over a cavity than any feign body.

Cavity-Pylon flame holder is an intrusive type flame holding device where the pylon is placed near the front wall of the cavity. It builds the mass trade between the cavity and the free stream [24]. It furthermore, enhances the mixing because of pylon generated vortex and shock associations [22].

Cavity based oscillations are undesirable since they prompt structural vibration and structure fatigue, high decibel noise, and sudden increment in the mean drag on the body which houses the cavity. Naudascher and Rockwell [2] have shown that Self-sustained vibrations in the cavity can be categorized into three groups first is ***fluid dynamic***, where oscillations emerge from the innate instability of the stream; secondly ***fluid resonant***, where motions are affected by resonant wave impacts (standing waves) and finally ***fluid elastic***, where motions are combined with the movement of a solid boundary. Figure 3 given below shows all the above mentioned oscillations.

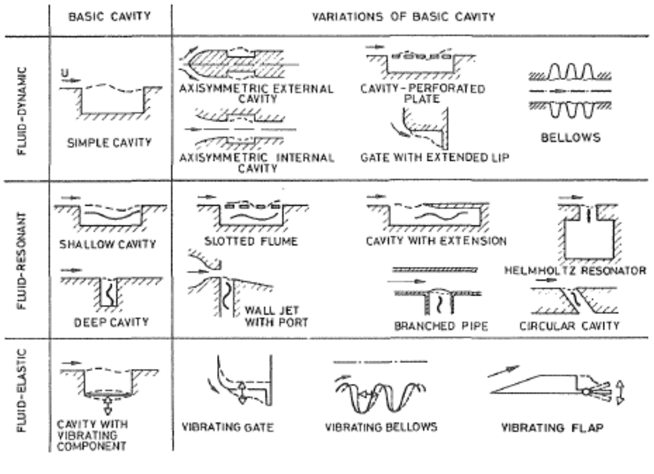


Fig. 3. Representative *fluid-dynamic, fluid-resonant, and fluid-elastic* types of cavity oscillations [2]

A. Fluid Dynamic Oscillations

Pure fluid dynamic motions occurs when the cavity length and the sound pressure wavelength is small and for the liquids, when surface wave effects are absent. Since we know that the increase in unsteady parameters in the shear layer of the cavity [25] is the basic mechanism for the generation of fluid-dynamic oscillations and the oscillations are strongly influenced by the presence of the rear wall of the cavity, so this type of oscillations can share some common parameters with the jet-edge type of oscillations[26]. Unlike the cavity geometry, the jet-edge oscillation is not constrained by mass conservation within an adjacent closed volume.

This fluid dynamic oscillations has two major mechanism that has been studied in details, firstly the conditions for amplification of shear-layer instability and secondly the feedback mechanism. Even after lots of research on cavity, concrete information on the propagation of disturbances in an initially turbulent free shear layer is lacking. Many predictive models were provided by earlier scientist like King et al. [27], Martin, Naudascher, and Padmanabhan [28], and Sarohia [29] and others but all these theoretical models failed to account for the time-dependent flow-impingement region, which later proved to be important in predicting amplitude of oscillations.

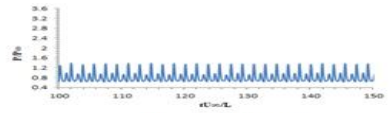
B. Resonant Cavity Oscillations

Resonant cavity oscillation is the self sustained cavity oscillations which are firmly combined with resonant wave impacts inside the cavity. Here the frequencies are adequately high and the relating acoustic wavelength is known to be of similar order of extent or lesser than the cavity characteristics length. When the cavity length to depth ratio is considerably large it is called Shallow cavity and when the length to depth ratio is considerably small it is called deep cavity. Shallow cavities generally contain longitudinal standing waves and deep cavities are characterized by transverse waves. Heller et al. [30] had defined that if L/D ratio is less than 1 it comes under deep cavity and when L/D is more than 1 it is called Shallow cavity.

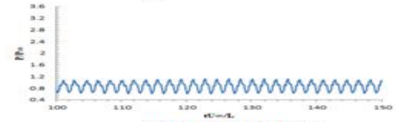
Apart from rectangular shaped cavity there could be different shaped cavities like Cylindrical cavities [31, 32], Triangular cavity [33, 34], The X-shaped cavity [35], Tandem cavities [36, 37], axisymmetric cavity [38, 39]. Xin Zhang and J. A. Edward [37] had experimentally studied observed when two cavities of same configurations are in Tandem, their unsteady pressure distribution and high frequency modes get altered whereas if two dissimilar cavities are put in tandem then their occurs small qualitative change in oscillation behavior.

Axisymmetric cavities are formed by rectangular cavity on a body of revolution. Mohri and Hillier [38] and J. Sinha [39] did comprehensive studies on Axisymmetric cavity and showed that there exists a pressure peak on the rear wall corner, where shear layer impinges on the cavity. Sinha [39] has also shown the significant reduction in pressure oscillations for L/D beyond 5. Static pressure time history graph has also shown that pressure oscillations on the trailing wall of the axisymmetric cavity are of larger magnitude than the front wall or the base of the cavity. Figure 4 gives the comparison of front wall corner, mid base and rear wall corner

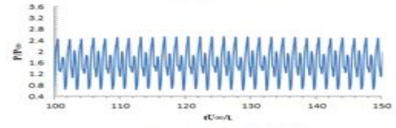
Pressure time history of static pressure for L/D = 1 axisymmetric cavity [40].



(a) Front wall corner



(b) Mid cavity base



(c) Rear wall corner

Fig. 4 Comparison of static pressure time history [40]

C. Fluid-Elastic Cavity Oscillations

When a wall or more than one walls of a cavity undergoes displacement and it is capable of exerting feedback control on the shear-layer perturbation amid the cavity vibration, the excitation is characterized as fluid elastic. Here the perturbed shear layer gets amplified in the similar fashion of vibrating structural resonance. Work done by earlier scientists also assumed that in Fluid-Elastic cavity oscillations, resonance frequency is greatly affected by the cavity Length-to Depth proportion (L/D). Because of the fluid structure phenomena interaction, the inertia, elastic, and damping characteristics of the structure comes into play and have a considerable influence on the overall flow oscillations. Goldman et al. [41] observed a random oscillatory motion of the elastically mounted flap for a free stream Mach number of 6. They showed that the flap vibrates at its natural frequency and the amplitude of vibration was some random function of time.

IV. NUMERICAL MODELING AND ANALYSIS TECHNIQUE OF CAVITY FLOW

Over a period of five decades researchers have used and developed various mathematical models to solve the flow field characteristics over different types of cavity under subsonic, supersonic and hypersonic region for both compressible and incompressible flow domain. Lots of researches and validation study has also been undertaken over lid driven cavity flow [42]. Lots of researches have been carried out on two dimensional and three dimensional cavities using steady and Unsteady RANS equations, Large Eddy Simulation (LES), Detached Eddy Simulation (DES), Direct Numerical Scheme (DNS), Proper Orthogonal Decomposition (POD) and Galerkin projection of the POD. These techniques have been discussed in this section.

P. Nayyar et al. [18] have modeled the weapon bay as a open type rectangular cavity of length-to-depth (L/D) proportion of 5 and width-to-depth (W/D) proportion of 1 at the Mach number of 0.85, using URANS, LES and DES. They have reported that DES and LES gave better frequency signature, noise and phase with experimental results than URANS for both the doors on and off condition. For doors-off condition Menter's baseline k-ω turrbulence model could capture the correct SPL curve.

With the advent in technology researchers are also using hybrid RANS/LES equations to model the flow. Shieh and Morris [43] had employed the similar coupled technique where the RANS equation in the boundary layer upstream of the cavity and LES was used for cavity flow analysis. Similar hybrid technique was used by Sinha et al. [44] where they formulated a new hybrid RANS-LES turbulence model to demonstrating cavity acoustics. The model joins a one-condition LES subgrid equation and a two condition RANS turbulence equation in a physically steady way. Larcheveque et al. [45] had applied the LES on the simulation of flow field over deep cavites for high Reynold's no. of 8.6 x 10^5. They observed the accurate predictions of all the fundamental frequency peaks. They also stated that LES can be utilized for complicated and highly detached flows. Supersonic analysis were carried out by N. Sinha et al. [46] for three dimensional cavity model using LES over a rectangular cavity with L/D of 4.5, L/W of 4.5 at Mach 2, and Reynolds no. 4.5 x 10^6, and for the same cavity Lockheed group [47] also did the simulation work on the same cavity at Mach 1.5. Lockheed group also validated their result with Euler method and they obtained that peak amplitudes give close agreement with experimental results. J. M. A. Lango [48] studied the application and of CFD based models in hypersonic conditions like re-entry vehicles etc. He had reported that RANS is fairly accurate when used for attached flow but often failed to solve the unsteady detached flow. LES scheme attempts to solve the smaller and more uniform scales while solving the high energy containing scales. DES model enjoys the advantages of both RANS and LES scales. H. Ludeke [49] has proved that DES can predict the hypersonic results more accurately. Chuangxin et al. [50] had developed the Dynamic Delayed Detached eddy simulation for turbulent flows based on the k-ω SST model and the dynamic k-equation subgrid model. Improved DDES model employs two coefficients C_k, and $C_{e,}$ which are computed dynamically based on the temporal and spatial variation of flow field at grid level and test filter level. They also showed that if turbulent Prandtl number model is mixed with DDES model it would give better result for wall heat transfer than dynamic LES model. V. Togiti et al. [51] applied DES, modified DES and DDES to a supersonic cavity of L/D=5.2 and L/W=5.8. They obtained that DES in all its form could capture the large scale vortical structure in the free shear layer and the shear layer break up. Zhou [52] had developed an immersed boundary method called Domain free discretization (DFD) for the application of RANS equation on turbulent flows. The immersed boundary method takes into effect the wall shear stress and zero penetration. The no penetration condition has been coupled with wall shear stress to calculate the velocity at the exterior nodes. The boundary conditions for SST k-ω model was determined analytically and then the turbulence parameters in the exterior nodes were calculated. SolKeun Jee and Karim Shariff [53] had developed the DES based on '$v^2 - f$' RANS model. The advantage of '$v^2 - f$' RANS is that it accounts for the anisotropy property in near wall turbulence which is not there in simple RANS. The DES coefficient is developed by taking into account both decaying and steady isotropic turbulence. Reddy et al. [54] had also developed a modified DDES scheme using the concept of eddy viscosity. They solved the problem of log-layer mismatch and with adoption of a clipped length scale coupled with eddy viscosity. We will now discuss about Direct Numerical Scheme (DNS) which solves entire range of turbulence from highest level to lowest level. Here high order difference schemes and many optimized explicit difference schemes coupled with high order Runge-Kutta Method could reduce the errors due to dissipation and dispersion of acoustic waves. These finite difference schemes were used in DNS. Colonius et al. [55] have unraveled the compressible Navier-Stokes conditions specifically for two-dimensional cavity with laminar boundary layers upstream. Many DNS schemes found applications with lid driven cavity flow [56]. A DNS approach solves the complete Navier's Stoke's equation including time derivative and non-linearity without any assumptions to prescribe boundary conditions. A complete flow field as a function of space and time is provided by DNS scheme. So grid counts should be increased and grid density should be improved for high Reynolds number flow. A lot of research is yet to be done on DNS as it can be the most accurate scheme once fully developed.

V. CAVITY OSCILLATION CONTROL

Lots of researches have been dedicated towards controlling the shear layer oscillations, vortex dynamics, pressure oscillations and aero-acoutics. Cavity flow control technique can be arranged into Active control and Passive control. Cateffasta et al. [57] has provided lots of information on Active and Passive controls of cavity and their classifications as shown in figure 5.

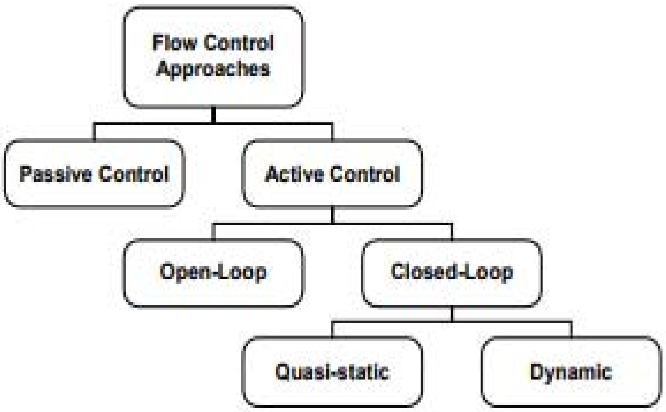


Fig. 5. Classification of flow control [57]

Closed loop control incorporates a feedback loop where some flow-field parameters are detected and send back to adjust the control signal. Open loop system offers no feedback loop. In Quasi-static loop, there is gradual change of control, mainly used when large time-scales for feed signal is used. Dynamic controls are used when time scales are in proportion. It is also used in real-time digital control systems. Shaw and Northcraft [58] had successfully used the Quasi-static loop for flow control. Williams et al. [59] had demonstrated the application of Dynamic control system. A feedback control system developed by DiStefano et al. [60] is shown in figure 6. Its basic mechanism and working form the basis of large researches in cavity flow suppression using Active control systems.

Lot of Active and Passive techniques have been developed for many years to control the cavity flow oscillations. Active control is the one where some external energy is provided to the cavity to modify its flow behavior. In Passive control only the shape and dimensions of the cavity is changed without any forced energy change. Some of the Passive techniques such as slanted trailing edge [61], passive venting system [62], leading edge saw teeth spoilers [63], passive external bleed system [64], porous walls ahead of front wall [65], static and oscillating fences [66], front wall inclination [39] etc., have successfully attenuated the cavity pressure oscillations. Similarly, many open loop and closed loop active devices have also succeeded in suppressing pressure oscillations. Some of the active techniques involve leading edge microjet injection [67], Piezoelectric bimorph actuator [68], leading edge piezoelectric flaps [69], powered resonance tubes [70], oscillating electromechanical [71], steady blowing [72], pulsed blowing [73], fluidic oscillating jets [74] etc.

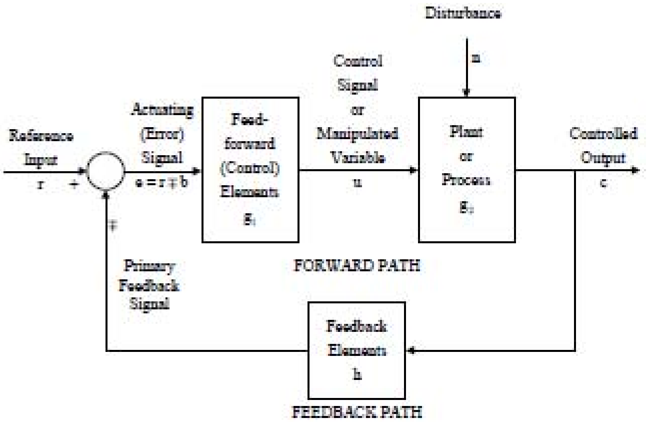


Fig. 6. Components of Feedback Control System [60]

VI. CONCLUSIONS

A comprehensive study has been undertaken to understand the types of cavities and the basic fluid dynamics, aero-acoustic and pressure oscillations over different types of Cavities. We observed that open cavities are mainly characterized by shear layer oscillations and vortex shedding from the leading wall of the cavity. A feedback mechanism, that works inside the cavity could explain the onset of the shear layer oscillations and unsteady pressure oscillations inside the cavity. Then we looked into different types of cavity oscillations based on the application of cavity at different places. We further observed different numerical modeling techniques and the application of turbulence model. Though RANS, URANS, LES, DES, DNS all have their share of merit and accuracy, but their application depends upon the flow condition, geometry and fluid-structure interactions. DES is a hybrid numerical scheme which has advantages of both LES and RANS and has reputation of modeling a problem accurately. We also looked into different Passive and Active control techniques to suppress the cavity noise. Now based on the knowledge gained we can design the numerical modeling scheme of a conical tandem type cavity.

REFERENCES

[1] S. W. Kang, J. M. Lee, and S. H. Kim, “Structural-acoustic coupling analysis of the vehicle passenger compartment with roof, air-gap, and trim boundary, ” J. Vibr. Acoust. **122**, 196 _2000.

[2] D. Rockwell and E. Naudascher, “Review-self-sustained oscillations of flow past cavities, ” J. Fluids Eng. 100, 152 1978.

[3] C. K. Tam and P. J. Block, “On the tones and pressure oscillations induced by flow over rectangular cavities, ” J. Fluid Mech. 89, 373 1978.

[4] J. Sinha, S. Das, P. Kumar and J. K. Prasad, “Computational Investigation of Control effectiveness in Near Transitional Open and Closed Axisymmetric cavity”, AASA, Vol.4, No.1, pp. 45-52, 2014.

[5] L. Cattafesta, D. R. Williams, C. W. Rowley, and F. Alvi, “Review of active control of flow-induced cavity resonance, ” AIAA Paper No. 2003-

[6] C. W. Rowley and D. R. Williams, “Dynamics and control of high-Reynolds-number flow over open cavities, ” Annu. Rev. Fluid Mech. **38.**

[7] Syed, A., “Detached Eddy Simulation of Turbulent Flow Over an Open Cavity With and Without Cover Plates”, Master of Science Thesis, 2010.

[8] Aradag. S. and Knight D., “Simulation of SupersonicCavityFlow Using 3D RANS equations, ” AIAA Journal, 2004.

[9] Lawson S.J. and Barakos G.N., “Review Of Numerical Simulations For High Speed Turbulent Cavity Flows, ” Progress in Aerospace Sciences, 2011, pp. 186-216, vol. 47.

[10] Aradag. S., “CFD for High Speed Flows in Engineering”, VDM Verlag Dr. Müller, 2008.

[11] Rossiter, J., "Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds., " Royal Aircraft Establishment, TR 64037, 1964.

[12] McCanless, G. F., and Boone, J. R., "Noise Reduction in Transonic Wind Tunnels, " *J. Acoustical Society of America,* Vol. 56, No. 5, Nov. 1974, pp. 1501-1510

[13] Woolley, J. P., and Karamcheti, K., "A Study of Narrow Band Noise Generation by Flow Over Ventilated Walls in Transonic Wind Tunnels, " AFOSR TR-73-0503, 1973.

[14] Betts, P. C, "Self-Induced Oscillations in an Open Water Channel with Slotted Walls, " *J. Fluid Mechanics,* Vol. 55, Part 3, 1972, pp. 401-417.

[15] Gerlach, C. R., "Vortex Excitation of Metal Bellows, "ASME *J.* Engineering for Industry, B'eb. 1972, pp. 87-94.

[16] Bass, R. L., and Holster, J. L., "Bellows Vibration with Internal Cryogenic Flows, " ASME *J. Engineering for Industry,* Feb. 1972, pp. 70-75.

[17] Ethembabaoglu, S., "On the Fluctuating Flow Characteristics in the Vicinity of Gate Slots, " Division of Hydraulic Engineering, University of Trondheim, Norwegian Institute of Technology, June, 1973.

[18] P. Nayyar, G. N. Barakos and K. J. Badcock, "Analysis and Control of Weapon Bay Flows", NATO RTO AVT-123 Symposium on 'Flow Induced Unsteady Loads and the Impact on Military Applications', Budapest 2005.

[19] J. Dahan, R. Futrzynski, C. Reilly, G. Efraimsson, "Aero-Acoustic Source Analysis of Landing gear noise via dynamic mode decomposition", The 21st International Congress on Sound and Vibrations, July 2014, China.

[20] Utsav Oza, Zhiwei Hu and Xin Zhang, "Effect of Cavity Flow on Landing Gear Aerodynamic Loads", 22nd AIAA Computational Fluid Dynamics Conference, AIAA-2015-2288.

[21] Chang Kee Kim, S. T. John Yu, and Z. Chang Zhang, "Cavity flow in Scramjet Engine by Space Time Conservation and Solution Method", AIAA Journal, Vol. 42, No. 5, 2004.

[22] Bogdanoff, D.W., "Advanced Injection and Mixing Techniques for Scramjet Combustors", Journal of Propulsion and Power, Vol. 10, No.2, Mar-Apr 1994, pp. 183-190.

[23] K. M. Pandey, P Kalita, K Barman, A. Rajkhowa and S.N.Saikia, "CFD Analysis of Wall Injection with Large Sized Cavity Based Scramjet Combustion at Mach 2", IACSIT International Journal of Engineering and Technology, Vol.3, No.2, 2011.

[24] Gardner, A Paull, A & McIntyre, "Upstream porthole injection in a 2-D scramjet", Shock Waves, vol. 11, pp.369-375, 2001.

[25] Rockwell, D., "Prediction of Oscillation Frequencies for Unstable Flow Past Cavities, " ASME JOURNAL OF FLUIDS ENGINEERING, Vol. 99, 1977, pp. 294-300.

[26] Woolley, J. P., and Karamcheti, K., "Role of Jet Stabilityin Edge-Tone Generation, " *AIAA J, ,* Vol. 12, No. 11, Nov.1974, pp. 1457-1458.

[27] King, J. L., Boyle, P., and Ogle, J. B., "Instability in Slotted Wall Tunnels, " *J. Fluid Mechanics,* Vol. 4, 1958, pp. 283-305.

[28] Martin, W. W., Naudascher, E. N., and Padmanabhan, M., "Fluid Dynamic Excitation Involving Flow Instability, " *Proc. ASCE, J. Hydraulics Div.,* No. HV6, June, 1975, pp. 681-698.

[29] Sarohia, V., "Experimental and Analytical Investigation of Oscillations in Flows Over Cavities, " PhD thesis, California Institute of Technology, 1975.

[30] Heller, H., Holmes, D., and Covert, E., "Flow-Induced Pressure Oscillations in Shallow Cavities, *J. Sound and Vibration,* Vol. 18, No. 4, 1971, pp. 545-553.

[31] Freestone, M. M., and Cox, R. N., "Sound Fields Generated by Transonic Flows over Surfaces Having Circular Perforations AD731-150, Aug. 1971.

[32] A. Rona "The acoustic resonance of rectangular and cylindrical cavities, Journal of Algorithm and Computational Technology, Vol. 1, No.3, October 2007, pp. 329-355.

[33] Torda, T. P., and Patel, B. 11., "Investigations of Flow in Triangular Cavities, " *AIAA,* Vol. 7, No. 12, Dec, 1969, pp. 2365-3267.

[34] Chin-Lung Chen and Chin-Hsiang Chen, "Numerical study of the effects of lid oscillation on the periodic flow pattern and convection heat transfer in a triangular cavity", International Communications in Heat and Mass Transfer 36(6): 590-596 · July 2009.

[35] I. Yahya, H. Harjana, and E. Mukowi, "Cavity Sound Pressure Enhancement of the Second Generation Power Generating Helmholtz Resonator with X-shaped Cavity Junction", 7th ICOPIA 2014, INDONESIA.

[36] C. H Woo, J. S Kim and K. H. Lee, "Analysis of two dimensional and three dimensional supersonic turbulence flow around tandem cavities", Journal of Mechanical Science and Technology, Volume 20, Issue 8, 2006, pp. 1256-1265.

[37] Xin Zhang, and J. A. Edwards, "Experimental Investigation of Supersonic Flows over Two Cavities in Tandem", AIAA Journal, Vol. 30, No. 5, 1992.

[38] K. Mohri and R. Hillier, "Computational and experimental study of supersonic flow over axisymmetric cavities", Shock Waves, Vol. 21, Issue 3, 2011, pp. 175-191.

[39] J. Sinha, "Studies on the Transition of the Flow Oscillations over an Axisymmetric Open Cavity Model", AASA, Vol. 3, No. 2, pp. 83-90.

[40] J. Sinha, S. Das, P.Kumar, and J. K. Prasad, "Studies on an Axisymmetric Supersonic cavity with Front wall inclinations", 15th AeSI CFD Symposium, August 2013, India

[41] Goldman, R. L., Morkovin, M. V., and Schumacher, R. N., "Unsteady Control Surface Loads of Lifting Re-entry Vehicles at Very High Speeds, " *AIAA J.,* Vol. 6, No. 1, Jan. 1968, pp. 44-50.

[42] T. A. AbdelMigid, K. M. Saqr, M. A. Kotb and A. A. Aboelfarag, "Revisiting the lid-driven cavity flow problem: Review and new steady state benchmarking results using GPU accelerated code", Alexandria Engineering Journal, Volume 56, 2017, pp. 123-135.

[43] C. M. Shieh and P. J. Morris, "Parallel computational aeroacoustic simulation of turbulent subsonic cavity flow", AIAA Paper 2000-1914, 2000

[44] S. Arunajatesan, and N. Sinha, "Hybrid RANS-LES Modeling for Cavity Aeroacoutics Predictions", International Journal of Aeroacoustics, Vol. 2, Issue: 1, 2003, pp. 65-93

[45] L. Larcheveque, P. Sagaut, I. Mary, and O. Labbe, "Large-eddy simulation of a compressible flow past a deep cavity", Vol.15, No.1, 2003.

[46] N. Sinha, S. Arunajatesan, and L. S. Ukeiley. High fidelity simulation of weapons bay aeroacoustics and active flow control. AIAA Paper 2000-1968, 2000.

[47] B. R. Smith, J. R. Jordan, E. E. Bender, S. N. Rizk, and L. L. Shaw. Computational simulation of active control of cavity acoustics. AIAA Paper 200-1927, 2000.

[48] J.M.A. Longo, "Modeling of Hypersonic flow phenomena", RTO-EN-AVT-116. 2004.

[49] H. Ludeke, "Detached Eddy Simulation of axial-symmetrical trailing currents with the DLR TAU code", Proceedings of the DGLR Fach Workshop der STAB, Göttingen, Germany, 2003. November 2003.

[50] Chuangsin He, Yengzheng Liu, and S. Yavuzkurt, “A dynamic delayed detached-eddy simulation model for turbulent flows”, Vol 146, 2017, pp. 174-189.

[51] V. Togiti, H. Lüdeke, M. Breuer, “Detached-Eddy and Delayed Detached-Eddy Simulation of Supersonic Flow over a Three-Dimensional Cavity”, Proceedings of the Seventh International ERCOFTAC Workshop on Direct and Large-Eddy Simulation, 2008, pp. 555-561

[52] C. H. Zhou, “RANS simulation of high-Re turbulent flows using an immersed boundary method in conjunction with wall modeling”, Computers and Fluids, Vol. 143, 2017, pp.73-89.

[53] SolKeun Jee and Karim Shariff, “Detached-eddy simulation based on the v^2-f model”, International Journal of Heat and Fluid flow, Vol.46, 2014, pp.84-101.

[54] K. R. Reddy, J. A. Ryon, P. A. Durbin, “A DDES model with a Smagorinsky-type eddy viscosity formulation and log-layer mismatch correction”, International Journal of Heat and Fluid flow, Vol.50, 2014, pp.103-113.

[55] T. Colonius, A. J. Basu, and C. W. Rowley, “Numerical investigation of the flow past a cavity”. AIAA Paper 99-1912, May 1999.

[56] E. L. Leriche, S. Gavrilakis, and G. Labrosse, “Direct numerical simulation of lid-driven cavity flow within a 3D inhomogeneous domain on an NEC-SX4 supercomputer”, Application of High Performance computing in Engineering, 2000.

[57] L. N. Cattafesta III, D. R. Williams, C. W. Rowley, and F. S. Alvi, “Review of Active Control of Flow-Induced Cavity Resonance”, AIAA 2003-3567.

[58] Shaw, L. and Northcraft, S., “Closed Loop Active Control for Cavity Resonance, ” AIAA, 99-1902, May 1999.

[59] Williams, D., Fabris, D., Iwanski, K., and Morrow, J., “Closed Loop Control in Cavities with Unsteady Bleed Forcing, ” AIAA 2000-0470, Jan. 2000.

[60] J. J. DiStefano III, A. R. Stubberud, and I. J. Williams, Feedback and Control Systems, Schaum’s Outlines, 2nd ed., McGraw-Hill, 1990.

[61] d§

[62] Perng, S. W., and Dolling, D. S., 2001, “Suppression of Pressure Oscillations in High-Mach-Number, Turbulent cavity flow, ” Journal of Aircraft, 38(2), pp. 248-256.

[63] Stallings, R. L., Plentovich, E. B., Tracy, M. B., and Hemsch, M. J., 1994, “Effect of Passive venting on Static pressure distribution in cavities at subsonic and transonic speeds, ” NASA TM-4549.

[64] Knowles, K., Khanal, B., Bray, D., and Geraldes, P., 2010, “Passive Control of Cavity Instabilities and Noise, ” 27th International Council of the Aeronautical Sciences, Nice, France, pp. 1-8.

[65] Zhang, J., Morshita, E., Okunuki, T., and Itoh, H., 2002, “Control of Closed type Supersonic Cavity Flow, ” 23rd International Council of the Aeronautical Sciences, Toronto, Canada, pp. 393.1-393.8.

[66] Md.Alam, M., Setoguchi, T., Matsuo, S., Tanaka, M., Md.Mamun, and Kim, H. D., 2006, “Attenuation of Cavity Pressure Oscillations in Two Dimensional Supersonic Flow by Passive Control” Proceedings of the 3rd BSME-ASME International Conference on Thermal Engineering, Dhaka, Bangladesh.

[67] Ukieiley, L. S., Ponton, M. K., Seiner, J. S., and Jansen, B., 2004, “Suppression of Pressure Loads in Cavity Flows, ” AIAA J, 42(1), pp. 70-79.

[68] Kurien, J., and Thangamani, V., 2010, “Control of Cavity Oscillation in Supersonic flow by Cavity floor microjet injection, ” Procedings of 37th National and 4th International Conference on Fluid Mechanics and Fluid Power, IIT Madras, Chennai, India.

[69] Kegerise, M. A., Cattafesta, L. N., and Ha, C., 2002, “Adaptive Identification and Control of Flow-Induced Cavity Oscillations, ” AIAA Paper, AIAA 2002-3158.

[70] Louis N. Cattafesta III, Song, Q., Williams, D.R., Rowley, C.W., Alvi, F.S., “Active control of flow-induced cavity oscillations”, Progress in Aerospace Sciences, 44, 2008, pp. 479-502.

[71] Raman, G., Kibens, V., Cain, A. B., and Lepicovsky, J., 2000, “Advanced Actuator Concepts for Active Aeroacoustic Control” AIAA Paper, AIAA 2000-1930.

[72] L. Shaw, S. Mc Granth, “Weapons Bay Acoustics-Passive or Active Control, ” AIAA 96-1617, April 1996.

[73] Grove, J., Leugers, J., and Akroyd, G., “USAF/RAAF F-111 Flight Test with Active Separation Control, ” AIAA 2003-0009, Jan.2003.

[74] Smith, B. R., Jordan, J. K., Bender, E. E., Rizk, S. N., and Shaw, L. L., “Computational Simulation of Active Control of Cavity Acoustics, ” AIAA 2000-1927, June 2000.

[75] Raman, G., Raghu, S., and Bencic, T. J., “Cavity Resonance Suppression using Miniature Fluidic Oscillators, ” AIAA 99-1900, May 1999.