Glimpses of aeroacoustic activities in India

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1. INTRODUCTION

Aeroacoustic research in India is a growing phenomenon, and has benefited from three major channels: (i) research in premier academic institutions like Indian Institutes of Technology (IITs) and Indian Institute of Science, Bangalore (IISc), focusing on theoretical aspects of aeroacoustic problems as well as basic experimental research; (ii) research and development in the government organizations and research labs such as Indian Space Research Organization (ISRO), Defence Research and Development Organization (DRDO), National Aerospace Laboratories (NAL), etc., focusing on aerospace/flow component development, aeroacoustic loading estimation, testing, etc.; and (iii) research in the form of sponsored research projects funded by organizations mentioned in (ii) to academic institutions with specific objectives. There has been a beneficial blend of theory, practice, and product development as a result of this synergy. The nature of work done in research and development establishments and in some academic institutes in India is reviewed in this article with specific reference to the facilities established for the work. The review is by no means exhaustive and is aimed to provide a flavor of the activities.

2. AEROACOUSTIC STUDIES FOR SATELLITE LAUNCH VEHICLES

Vikram Sarabhai Space Center (VSSC) has been carrying out experimental and theoretical analysis of acoustic loading characterization and pseudo acoustic excitations during launch and atmospheric regimes of rocket flight.

Experimental studies are carried out for shock boundary layer interaction during the transonic and supersonic phase of flight with strap-on boosters. Flow visualization is used to identify the locations for conducting acoustic and unsteady pressure measurements. Figure 1 shows oil flow visualization for a 20° boat tail angle at Mach 2 and Reynolds number of 4×10^6 [1]. The zones of separation and reattachment are illustrated. The unsteady pressure measurements indicate that the

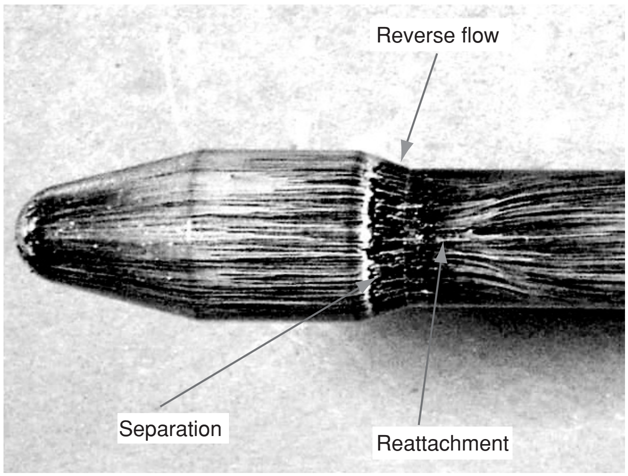


Figure 1: Oil flow visualization of bulbous nose-cone.

fluctuating pressure coefficient increases along the axial direction of the separated zone and peaks at the reattachment point.

Launch vehicles experience highest jet noise level during lift-off. The lift-off noise is predicted using Discrete Source Allocation Technique (DSAT) [2]. The predicted values of 1/3rd sound pressure spectra on heat shield compare well with flight measurements (Fig. 2).

Very high acoustic levels are registered during ignition transients of rocket motors. Detailed acoustic measurements are carried out in the mobile anechoic chamber at IIT, Kanpur [3, 4]. The chamber dimensions are 2 × 2 × 3 m (l × b × h). The cut-off frequency of the chamber is 630 Hz. It is found that the acoustic level measured is very high when a nozzle is operated at Nozzle Pressure Ratio (NPR) of 2 (ratio of settling chamber pressure to the back pressure). The narrow band sound pressure spectra measured at three locations in the upstream direction of the nozzle are shown in Fig. 3. They contain the fundamental tone and its higher harmonics.

At lift-off and during low subsonic portions of the flight, the acoustic and pseudo acoustic excitations result from the propulsion system generated noise field surrounding the vehicle. In the transonic and supersonic regimes of flight, aerodynamically generated acoustic field is incident on the vehicle. They induce random vibrations in launch vehicle structures and are responsible for transmission of the acoustic field on to the systems contained within.

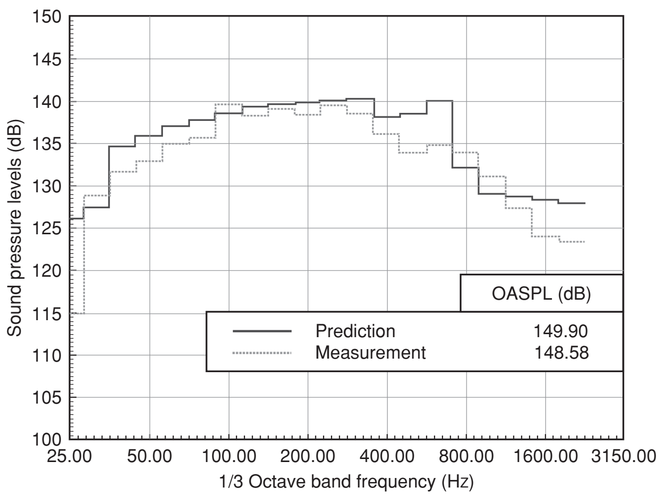


Figure 2: Comparison of predicted jet noise levels with flight measurement (heat shield).

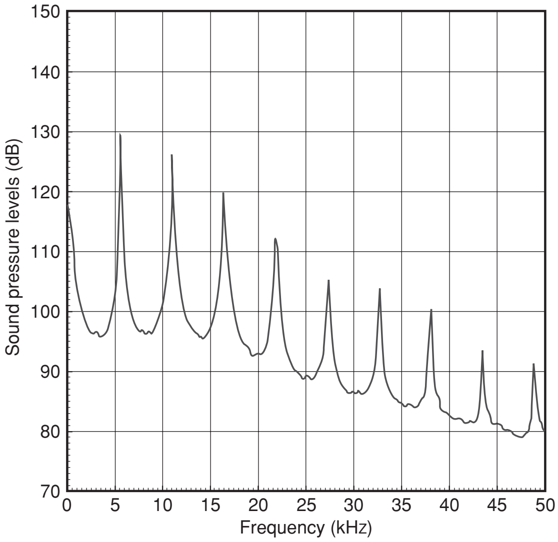


Figure 3: *Narrow band sound pressure spectra in the upstream direction of a nozzle operated at NPR = 2.*

The launch vehicle and its vicinity experience very high sound pressure levels during take-off. The attenuation through water injection was studied in simulated subscale tests at the Satish Dhawan Space Center (SDSC) in Shriharikota. Figure 4 shows water injection with twin jets.

Noise at different parts of a launch vehicle was measured in a small-scale model of a launch pad and noise suppression system. Measurements were done during the vertical lift-off trajectory. The primary source of noise is the two jets emerging from the base of the launch vehicle at a Mach number of about 3.4. The simulation of water injection corresponded to the different locations in the launch pad such as the upstream and downstream edges of the jet deflector cover-plate, bottom and top of the launch pedestal and at different locations on the service structure. The effect of staged injection of water was also studied. The reduction in the overall sound pressure level with hot jets is shown in Fig. 5. The reduction in the overall sound pressure level was about the same for hot jets in the temperature range between 600 and 1200K.

Figure 4: *Water injection in twin jets simulating strap-on rockets.*

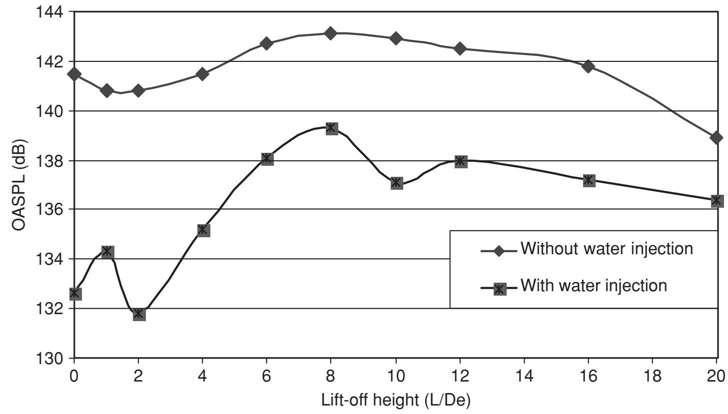


Figure 5: Reduction of sound pressure level due to water injection.

3. ACOUSTIC TEST FACILITIES

Acoustics tests for the prototype models of launch vehicle and satellite components are done in Acoustic Test Facility (ATF) at NAL, Bangalore. The ATF has a reverberation chamber of 1100 m^3 (10.33 m × 8.2 m × 13 m) in which a maximum sound pressure level of 157 dB (ref 20 μPa) can be generated. The chamber with a typical test specimen is shown in Fig. 6. The facility is capable of simulating the spectra for satellites and launch vehicles within the tolerance band specified by the respective agency. Vibration and strain measurements on spacecraft, launch vehicle stages and their sub-systems are also carried out during the tests.

The facility has also been used by VSSC for developing acoustic blankets for payload fairings. The absorption characteristics were evolved through sub-scale model comprising 1 m diameter cylindrical shell. Acoustic excitation of 157 dB (OASPL) was imparted to test specimen. Acoustic

Figure 6: Satellite system in reverberation chamber at NAL, Bangalore.

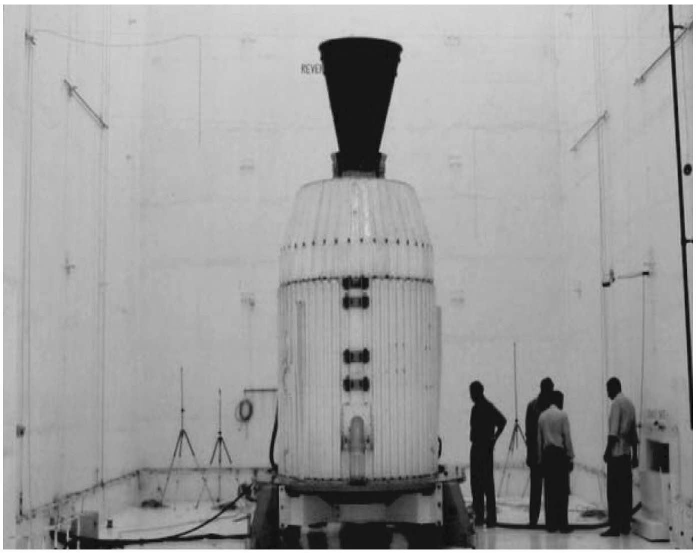


Figure 7: *Engine bay assembly in ATF.*

blankets of different thicknesses were tested for their absorption characteristics. The blankets were covered with teflon coated fibre glass cloth. Parametric studies yielded optimal configurations of material, dimensions, and deployment on acoustic absorption. A maximum attenuation of 18.2 dB was seen for a bulbous metallic heat shield for an externally impressed acoustic field of 155 dB. Dynamic characterization tests of the interstages with the packages mounted in them, flight data verification tests, and flight acceptance tests were also carried out by VSSC in the ATF [5]. Figure 7 shows the engine bay assembly in the facility.

A jet noise generator has been developed capable of producing high frequency random noise above 2 kHz, for which no high level generators are available. This device, shown in Fig. 8, is ideally suited for the simulation in reverberation chambers due to the randomness of the acoustic energy generated. Random noise in the range of 2 – 8 kHz, up to 140 dB amplitude is generated in the reverberation chamber. This also finds applications in high frequency noise environment testing for aerospace and automobile industries.

An acoustic test facility which can generate an overall sound pressure level of 160 dB and record 260 channels of vibration, strain, and acoustic data has

Figure 8: *Jet noise generator of NAL.*

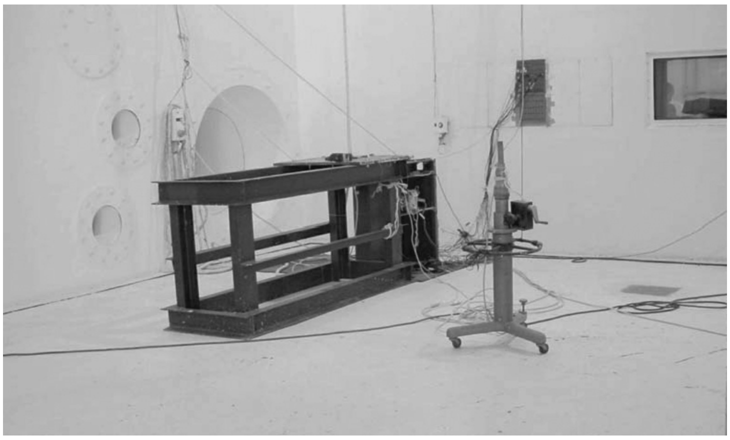


Figure 9: Acoustic reverberation chamber of DRDO.

been developed by DRDO, Hyderabad. The facility is used for dynamic tests of fully integrated aerospace systems. The size of the reverberation chamber is 8.25 × 6.25 × 10.35 m and the range of frequencies is 65 Hz to 100 kHz. A view of the chamber is given in Fig. 9.

4. NOISE FROM TRANSIENT JETS AND COMPRESSIBLE VORTICAL STRUCTURES

The noise associated with the formation, interaction and decay of transient compressible vortical structures has been pursued at the Aerospace Engineering Department at IIT Kanpur. The base element of the facility is an open ended shock tube 64 mm in diameter with a driver section having a maximum length of 300 mm and a driven section with a maximum length of 1200 mm. The noise generated from an isolated compressible vortex element and its interaction with transient flow fields is determined. Nozzles of different shapes are used to create non-circular vortex rings. The schematic of a single shock tube setup is shown in Fig. 10.

The formation and propagation of a vortex for shock Mach number of 1.3 is shown in Fig. 11. The events of transient flow processes such as formation of vortex ring, roll of separated shear layer at the lip of the shock tube exit and the detachment are interpreted. Two tubes are used to study the interaction of a vortex ring with a shock and vortex-vortex interaction as shown in Fig. 12. An appropriate object is positioned at a downstream location from the exit of the shock tube to determine the interaction of vortical structures with surfaces.

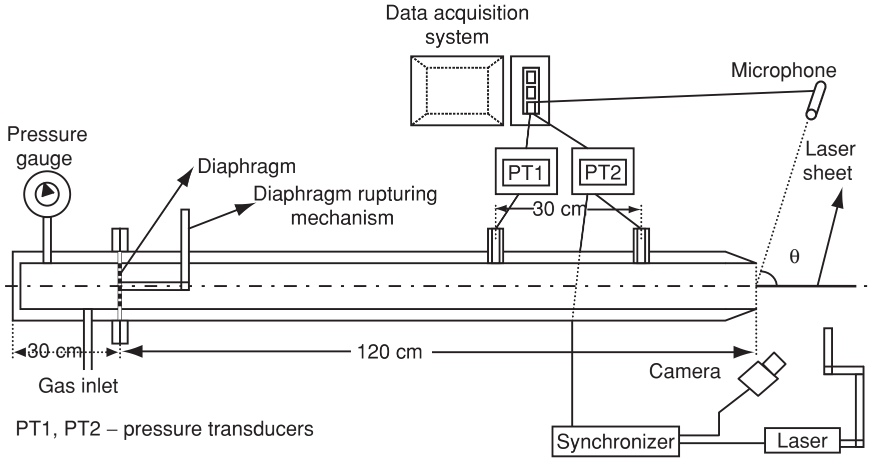
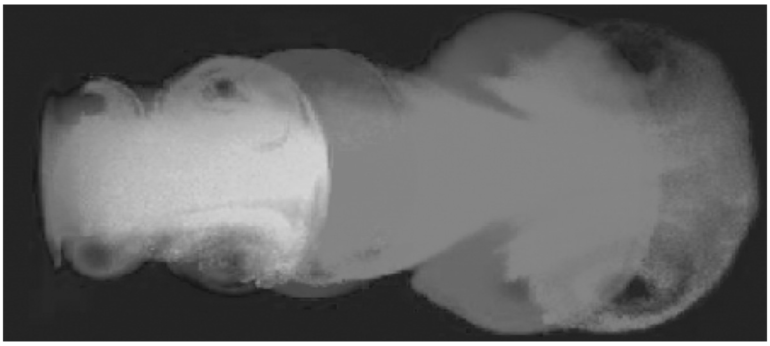


Figure 10: Schematic of the vortex-ring-generator with associated equipment for flow visualization and noise measurement.



igure 11: *Formation and temporal evolution of a vortex ring for shock Mach number of 1.3.*

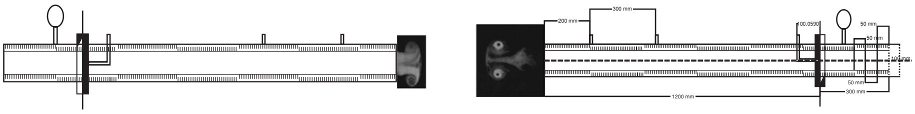


Figure 12: *Schematic of experimental facility for studying vortex-vortex and shock-vortex interactions of variable strengths at different angles.*

FFigure 13: *Aerodynamic noise studies on control valve and a view of the anechoic chamber at FCRI.*

5. NOISE RADIATION FROM VALVES

The aerodynamic noise characteristics of flow devices and silencers are measured in the hemi anechoic chamber at the Flow Control Research Institute (FCRI) at Palghat. This is a specially built free field environment over a reflecting plane satisfying the requirements of ISO 3745. Regulated air supply at 20 bar is also available adjacent to this chamber. The internal view of the facility is shown in Fig. 13.

The chamber is 8.5 × 8.5 × 4.5 m. The lower cut off frequency is 100 Hz. The ambient sound pressure level is less than 20 dB (for octave band centre frequency above 125 Hz). The expected standard deviation of reproducibility in determining sound power level of sources by using this facility is 1dB.

6. FLOW CONTROL WITH HARTMANN WHISTLE

The intense acoustic radiation, the discrete nature of the frequency spectrum and the strong directivity of the radiation of a Hartmann whistle are studied at the Department of

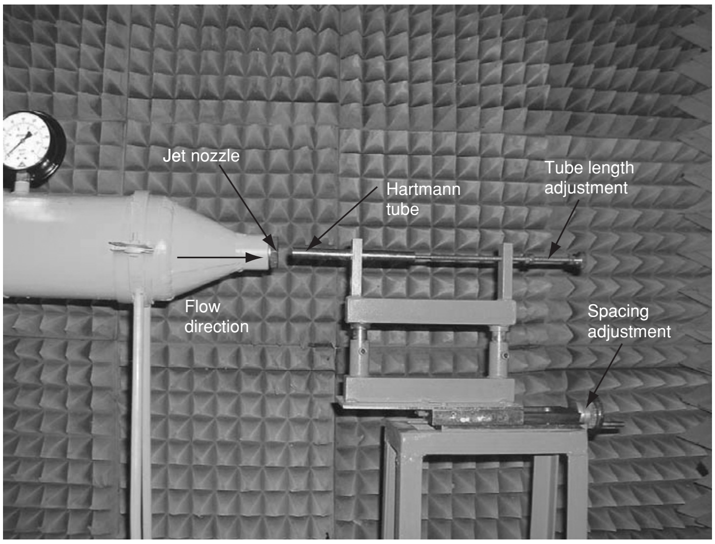


Figure 14: Hartmann whistle in anechoic chamber.

Mechanical Engineering, IIT Madras. A semi-anechoic chamber has been used for the experiments. The Hartmann whistle in the anechoic chamber is shown in Fig. 14. A comparison of whistle noise with a free jet at an angle of 37° to the axis of the jet for the same exit conditions is shown in Fig. 15.

The whistle was characterized for its performance in terms of its frequency, amplitude, acoustic power, efficiency, and the overall and tonal directivities. Strong directivity in the downstream direction was demonstrated. A typical plot of the directivity is shown in Fig. 16. The unsteady shock structure driving the noise is shown in Fig. 17. The interaction of the intense acoustic radiation with single droplets and sprays is being evaluated. Figure 18 gives the deformation of a single droplet at three different instants of time when subjected to an overall sound pressure level of 150 dB. Distortion of droplets and formation of satellite droplets were also observed. Modeling is under progress.

7. AERO-THERMO-ACOUSTIC RESEARCH

A number of laboratories are involved in studying mode switching in dump combustors and interaction of acoustics and combustion. The problem of vortex shedding-induced oscillations in segmented solid propellant rockets is being modeled in the Department of Aerospace Engineering, IIT Madras. The influence of flexible flaps on vortex shedding is studied at the Department

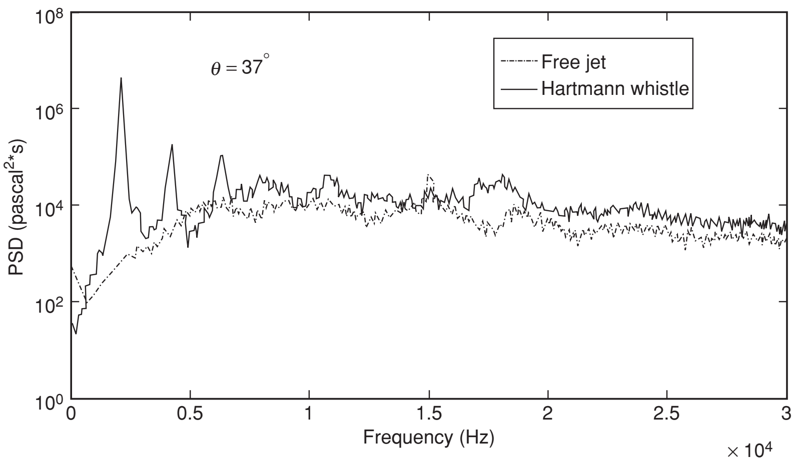


Figure 15: Comparison of the spectra of Hartmann whistle and free jet.

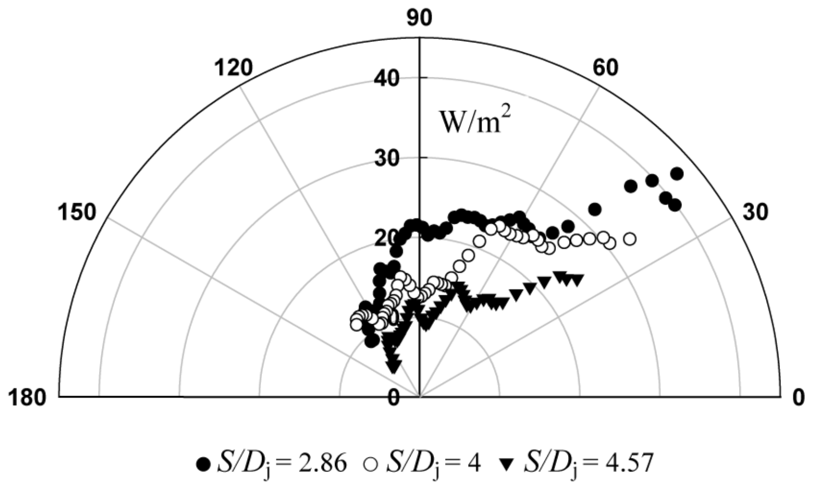


Figure 16: Acoustic directivity at different stand-off distances.

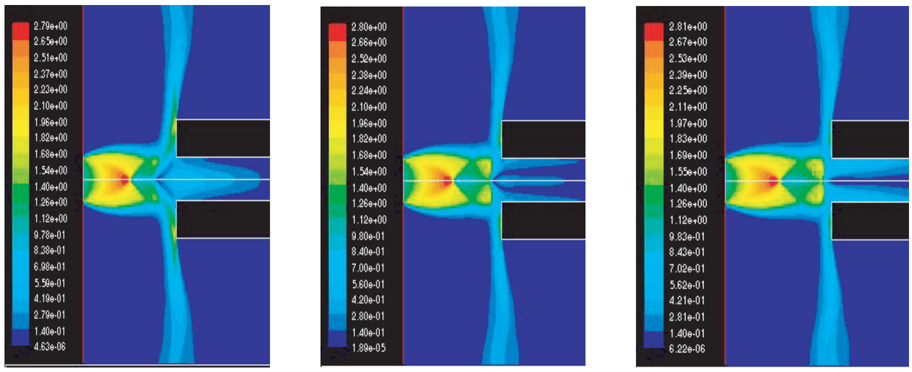


Figure 17: Unsteady shock structure obtained at different times.

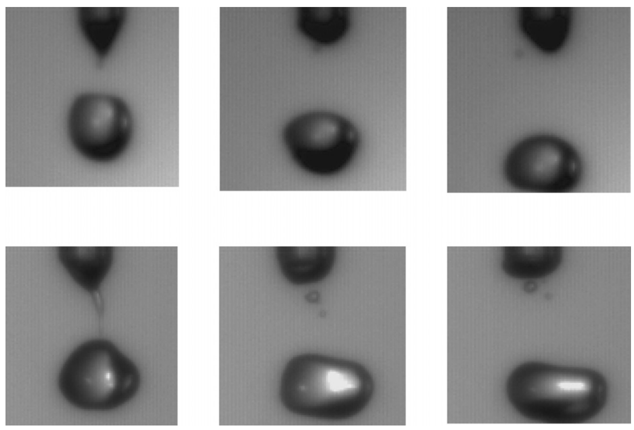


Figure 18: Evolution of droplets with and without acoustic field.

of Mechanical Engineering, IISc, Bangalore. Studies on mode switching (vortex shedding modes and standing wave modes) in dump combustors with and without combustion and with flame stabilization devices are pursued in the Departments of Aerospace Engineering at IIT Madras and IIT Kanpur. Experiments at IIT Kanpur on a bluff body stabilized model- combustor fitted with variable length inlet showed the combustion to dampen the inlet acoustic disturbances. Non-circular jets were also studied at IIT Kanpur for noise reduction and mixing enhancement. Polygonal jets of low orders were found beneficial for both mixing enhancement and noise reduction [6, 7].

Flow and flow-visualization data

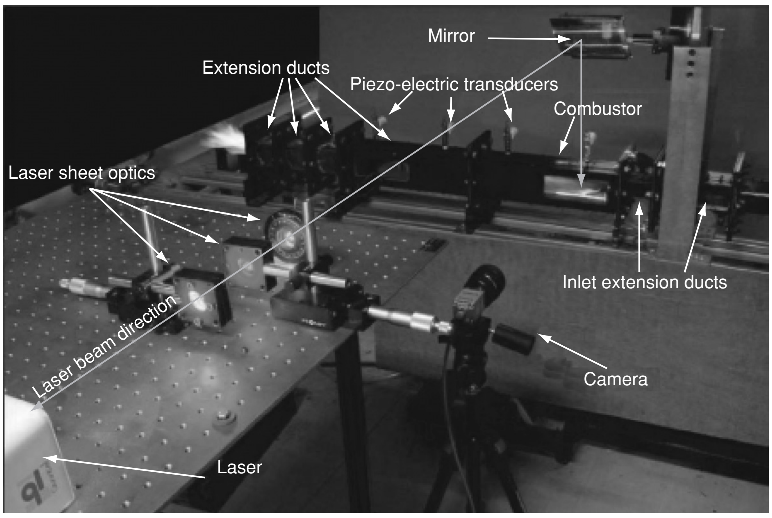


Figure 19: *Laser diagnostics for aero-thermo-acoustics.*

from planar laser diagnostics is used to support the acoustic analysis of combustion systems. Figure 19 shows the rig used for the acoustic analysis of combustion systems at IIT Madras. The study of combustion-acoustic interaction showed that the interaction is both non-normal and nonlinear [8]. Nonnormality leads to short time amplification even though the individual modes decay exponentially. This transient growth can trigger nonlinearities when the amplitude of the fluctuations is sufficiently large. The various eigenmodes of the coupled linearized combustion-acoustic system interact resulting in the growth of oscillations, even when the eigenvalues indicate stability. Nonlinear interaction of diffusion flames with acoustic oscillations is also investigated [9]. An algorithm is developed for determining oscillatory heat release from acoustic pressure measurements [10]. The unsteady response of premixed flames is also investigated [11]. Pure loud tones are shown to significantly influence the divergence characteristics of gaseous jets [12]. Experimental investigations of the interaction of sprays with acoustic fields are performed using Particle Image Velocimetry (PIV) [13] and Phase Doppler Particle size Analyzer (PDPA).

The attenuation characteristics of screech liners have been investigated at the Gas Turbine Research Establishment (GTRE) at Bangalore for an afterburner. Figure 20 shows the

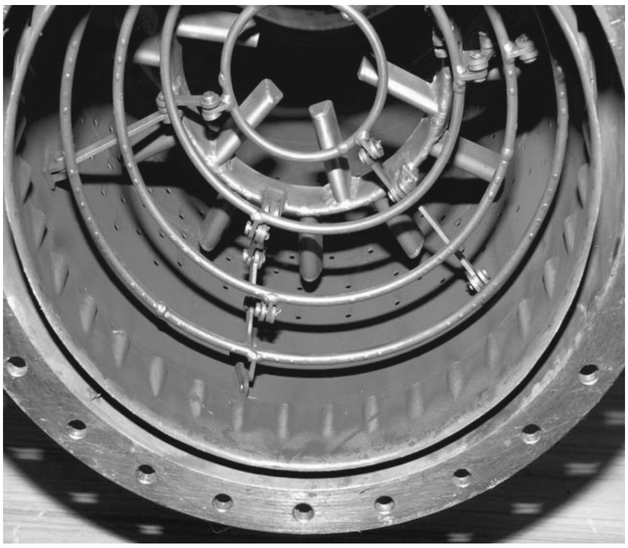


Figure 20: *Screech liner in the afterburner.*

screech liner in a scaled afterburner. The role of porosity of the screech liner was investigated. Figure 21 shows the afterburner integrated with the test facility. A liner porosity of 2.5% gave significant attenuation in the sound pressure level. The results are shown in Fig. 22.

Facilities for study on jet noise have also been set up at the Aeroacoustics and Plasma Dynamics Laboratory of the Department of Aerospace Engineering, IISc, Bangalore. Jet velocities from low subsonic to Mach 3 are generated. Over-expanded as well as under-expanded jets have been investigated. Jets with and without impingement have been tested for aerodynamic noise [14, 15]. Stagnation pressures of up to 100 atmospheres may be generated in this facility.

8. ACTIVE NOISE CONTROL (ANC)

Cabin noise control in cockpits and helicopters is pursued at NAL, Bangalore. Figure 23 shows an ANC system used in an aircraft cockpit mock-up model of volume 3 m^3. The error microphones were placed behind the seats and the secondary sources (loud speakers) were fixed above the seats. A reduction of 21 dB and 18 dB were observed at two microphone locations for a tonal excitation of the cockpit at 180 Hz, 80 dB.

The use of active adaptive headsets was also studied at NAL, Bangalore. Fighter aircraft cockpits suffer from severe noise problem (110 dB). A two channel algorithm was implemented on TI TMS320C6701 processor for a band limited white noise at 96 dB. It resulted

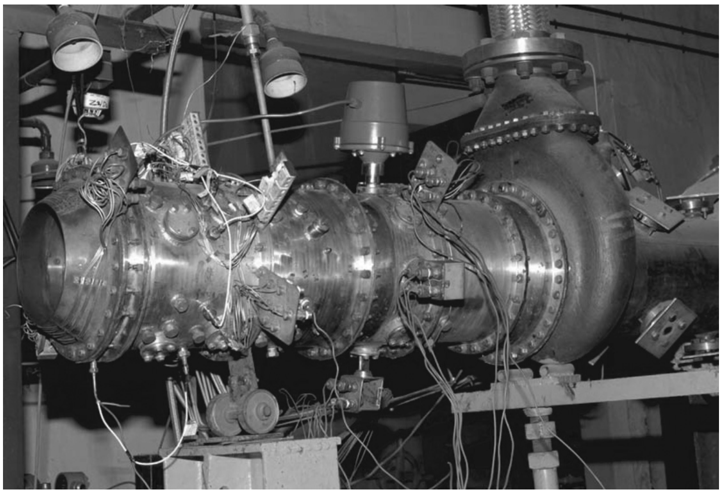


Figure 21: Afterburner integrated for test.

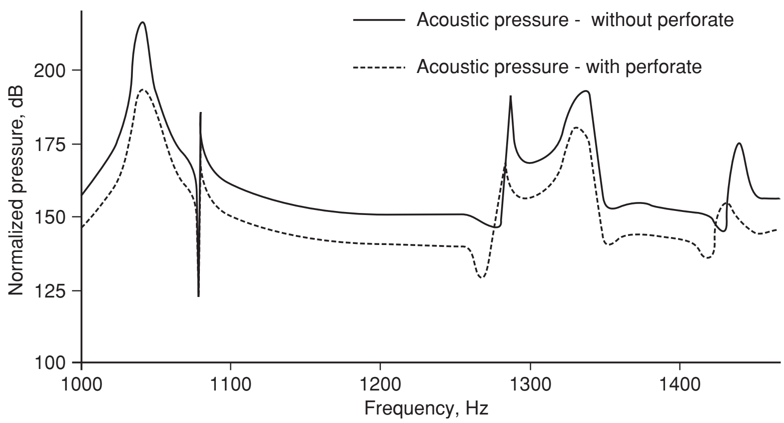


Figure 22: Comparison of acoustic pressure with and without perforate.

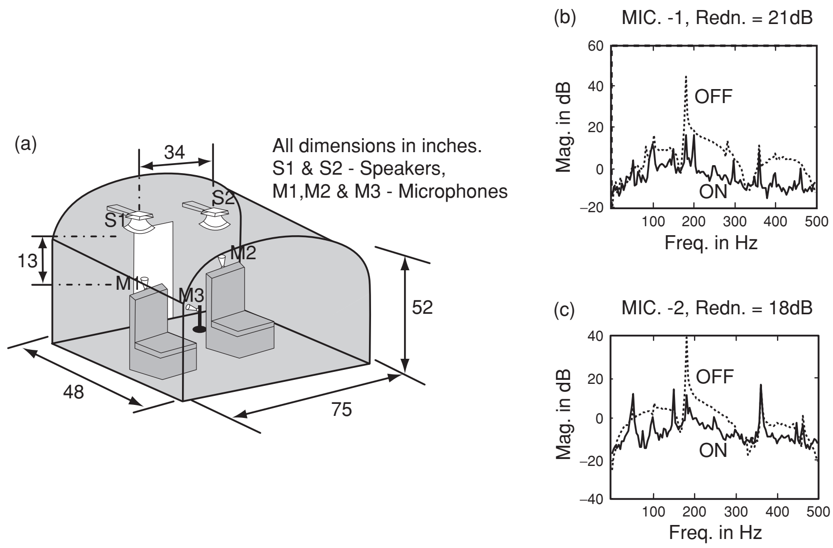


Figure 23: ANC for cockpit noise reduction and Power Spectral Density (PSD) for ANC Error.

in a reduction of 12.56 dB and 14.81 dB, as shown in Fig. 24 [16, 17].

9. ACOUSTICS OF DUCTS AND MUFFLERS

For over three decades, research and development work has been carried out at the Department of Mechanical Engineering at IISc, Bangalore on the analysis and design of mufflers with application to the exhaust and intake systems of automotive engines, gensets, compressors, fans and the HVAC (heating, ventilation and air-conditioning) systems. A comprehensive transfer matrix method has been developed for the absorptive as well as reactive mufflers or silencers [18]. Transfer matrices have been developed for over 50 different elements constituting efficient commercial mufflers. A novel Volume Synthesis (VS) algorithm has been developed for

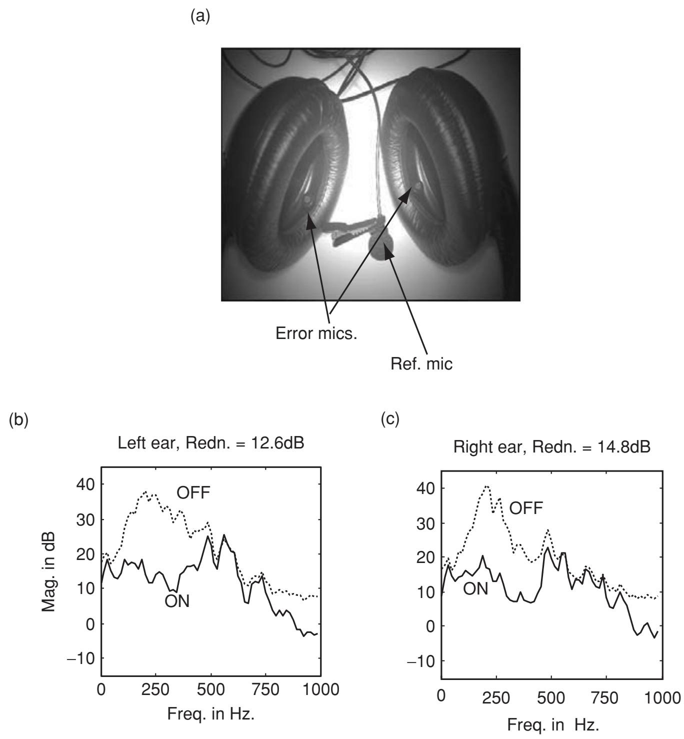


Figure 24: Active adaptive headset with PSD of ANC error.

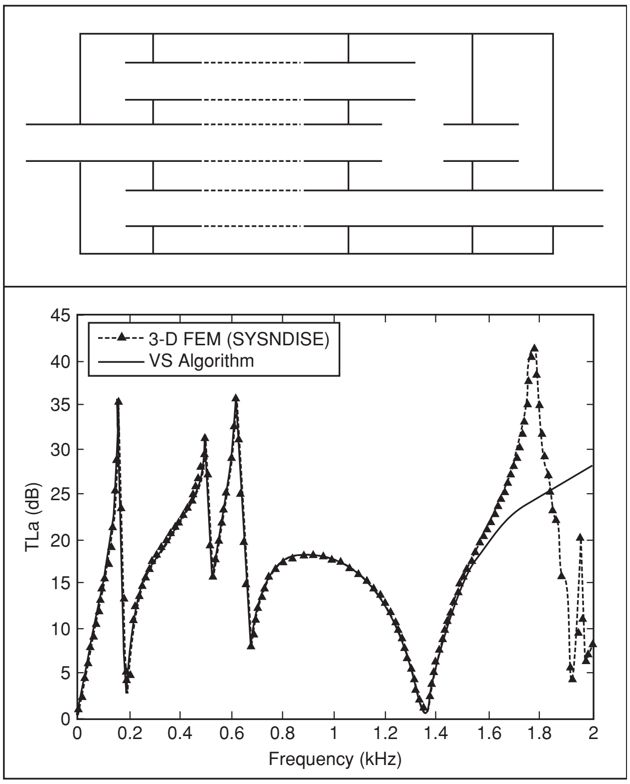


Figure 25: Validation of the VS algorithm.

analysis of the multiply-connected muffler elements (see Figs. 25 and 26 for two configurations) [19]. Making use of the multiple loads method, the AVL-BOOST software for time-domain CFD of the engine, and the results from extensive parametric studies, comprehensive empirical expressions have been derived for the aeroacoustic source characteristics of the intake as well as exhaust systems of turbocharged as well as naturally aspirated engines. A Graphical User Interface (GUI) has been prepared for designers who may not have any training or expertise in duct acoustics and yet wish to analyze a given or proposed muffler configuration for the insertion loss as well as the unmuffled sound pressure level radiated from the tail pipe of a particular engine.

Reactive mufflers work well at relatively low and mid-range frequencies whereas absorptive mufflers work at mid-range and high frequencies. So, combination muffler configurations [20] have been designed and analyzed to cover a wide range of frequencies, as indicated in Fig. 26.

10. CONCLUDING REMARKS

This lead article presents an overview of the aeroacoustics research, development and testing carried out in India, with emphasis on the more recent work. The national laboratories of ISRO, DRDO and the Council of Scientific and Industrial Research (CSIR) have been concentrating on testing and development work related to aeroacoustics of launch vehicles during the launch and atmospheric regimes of the rocket flight and noise control. Substantial work has been done in flow visualization, numerical prediction (making use of CFD) and measurement of acoustic field generated, and the consequent random vibrations of the launch vehicle structures. Measurement and suppression of the aerodynamic noise (jet noise) have also been investigated. Acoustic test facilities have been designed and used extensively for the prototype and scale models of launch vehicle and satellite components. Concurrently, basic and applied research has progressed on transient compressible vortical

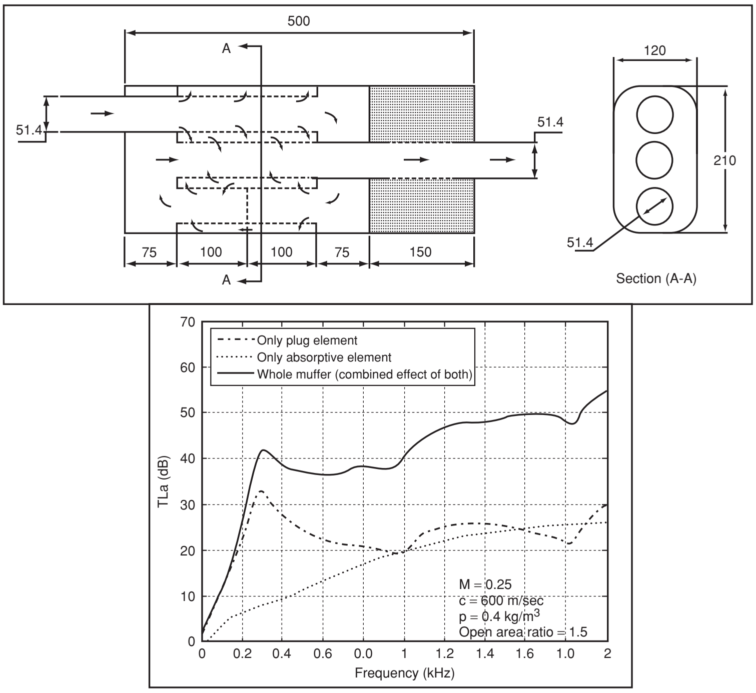


Figure 26: Generic muffler configuration and its performance.

structures, Hartmann whistle, interaction of acoustics and combustion, screech liners, active noise control, duct acoustics, design of mufflers or silencers, etc. Most of the work is documented in the in-house reports, while some of it has been published in archival journals. Significant progress has been achieved in obtaining input data for design of components and subsystems for the different applications involving generation, propagation and attenuation of aerodynamic noise.

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OMAHA'S NOISE LAWS ARE UNCONSTITUTIONAL (AND PROBABLY RACIST TOO)

The American Civil Liberties Union has called Omaha's new nighttime noise ordinances illegal and said if the city tries to enforce them, both sides will be headed to court. The new laws were introduced in November, but have yet to be used. Police call them an important tool to help them break up crowds and keep people safe, but the ACLU insists the city is trying to address "a routine law enforcement problem" by sacrificing the rights of law-abiding citizens. City Council President Dan Welch has argued: "If people are outdoors between 1 and 6 in the morning and they're disturbing the peace or making excessive noise, the police should have the right to disperse that crowd," he said. But the ACLU calls the measure both illegal and unenforceable. "They're criminalizing people who just happen to be standing by while someone else violates the law," said ACLU Legal Director Amy Miller. Another ordinance would make a business a "nuisance" if there were a large, noisy crowd outside in the middle of the night. "Both of these ordinances are tied to criminal activity, so it's more than just as the ACLU describes it, there has to be something else going on that creates a disturbance," said Omaha's city attorney Paul Kratz. Kratz believes both ordinances will stand up in court. But that's not the ACLU's only concern. "We have a deep suspicion that the city of Omaha if they are enforcing these ordinances are going to be doing it in primarily minority neighborhoods. We just don't see them driving out to west Omaha to harass people in mostly white neighborhoods," Miller said.

NOISE ABATEMENT ORDERS STEADILY IGNORED

Lawyers want to serve an anti-social behaviour order on a noisy neighbour whose late-night parties and yobbish behaviour have made life a misery for his street. People living near Peter Calvin Thomas Gillett in Earl Street, Colne, had to put up with disturbances until dawn, doors banging and heated arguments, Reedley magistrates were told. One young couple had to send their young baby to sleep with relatives because the youngster was getting no rest, the court heard. Gillett, 23, was first convicted of 24 breaches of a noise abatement notice last September, after an investigation by Pendle council. He was fined £450 with £100 costs by magistrates but continued to cause problems for his neighbours. Howard Culshaw, prosecuting for Pendle council, said following the new complaints, Gillett was served with a new noise abatement notice by environmental health officer Kenneth Eddington. But neighbour Anthony Watson complained that the parties, sometimes taking place through the night until daybreak, had carried on. Mr Watson, who had a wife and baby son, kept a diary of the noise nuisance, which he says took place on at least five occasions between October and November last year. Problems ranged from loud music being played throughout the day and night at excessive levels, shouting and screaming. He told council officers in a statement: “I am very tired, as is the rest of my family, due to the noise and our lack of sleep.” Magistrates found Gillett guilty of five breaches of a noise abatement notice in his absence. He claimed he could not attend the court case, as he was working.

SPAIN BAR OWNER JAILED OVER NOISE

A Barcelona bar-owner has been jailed for five and a half years for injuring her neighbours with loud music. It is the stiffest sentence ever imposed in Spain for such an offence. Three people had suffered grave damage to their physical and mental health as a result of living next to the Donegal pub in Las Ramblas, the judge ruled. Maria del Carmen Ahijado’s unlicensed sound system had pumped out music from five speakers from 0900 to 0300 daily at levels in excess of the legal limit. Ms Ahijado, who was also fined more than 17,000 euros ($22,000), had ignored several previous orders to turn the music down. The judges described the noise, played from early morning until half-way through the night, as a form of torture. One neighbour had to seek treatment for anxiety, depression and insomnia.

ANOTHER CLASS ACTION COMING ROUND THE MOUNTAIN

A former Norfolk Southern Railway Company employee claims on-the-job noise pollution caused permanent injuries to his ears. On March 4, Sherman A. Yates sued Norfolk Southern in Madison County Circuit Court. He is seeking a judgment of more than $50,000, plus costs. Yates claims that throughout his railroad career, from 1974 until 2008, he was subject to noise pollution. In addition to his ear injuries, Yates suffered injuries to his auditory system, suffered great pain and mental anguish and lost money and earning he would have been entitled to, the suit states. He claims his earning capacity has been greatly diminished and he has incurred medical expenses. Norfolk Southern was negligent by failing to provide safe tools, by failing to furnish Yates with necessary equipment to perform his job and with necessary personal protective equipment, by failing to provide Yates with proper supervision, by failing to warn Yates of hazardous conditions and by allowing unsafe practices to become standard, according to the complaint. The company also negligently assigned Yates work it knew would result in his injury, assigned him duties that it knew were beyond his physical capacity, failed to provide a safe work place and failed to provide safe work methods, the suit states.