75 YEARS DEPARTMENT OF AEROSPACE ENGINEERING

Indian Institute of Science

भारतीय विज्ञान संस्थान

A CELEBRATION

Snippets from the IISc Archives

FOREWORD

In 1942, in the midst of the Second World War, the Department of Aerospace Engineering was founded under the leadership of Prof VM Ghatage, an outstanding aviation engineer, to help the recently established Hindustan Aeronautics Ltd (HAL) in the British war effort. It has since come a long way.

Over the past 75 years, the Department has served the nation by nurturing many aerospace establishments within the country. In the early years, it was the backbone of Defence Research and Development Organisation (DRDO) and helped it develop many military technologies. In early 1960s, it started the Rocket and Missiles Programme as a part of Integrated Guided Missile Development Program (IGMDP) and trained many students in this area, many of whom went on to occupy senior leadership positions in DRDO. The Department's former Chairperson, Prof Satish Dhawan, who would go on to become IISc's Director, was instrumental in starting the Space Commission which has shaped the country's indigenous space programme. He was also the head of ISRO, and he contributed in no small measure to make it what it is today: one of the leading space agencies in the world.

The Department's contributions to Light Combat Aircraft (LCA), the Chandrayaan mission and the Mars Mission are well known and well documented. What may not be as well known is its expertise in the design and operation of wind tunnels.

In 1942, under Prof Ghatage's leadership, the Department constructed the country's first closed-circuit tunnel. In 1959, it commissioned the first open-circuit wind tunnel. Designed by the Department's own faculty, it was considered an engineering marvel. This wind tunnel, the largest of its kind in India, continues to serve the nation to this day. In recent decades, the Department has built more than 20 additional sophisticated tunnels for different speed ranges, an achievement no other academic institution in the world can boast of.

The Department has also made impressive academic strides. It is rated as the best aerospace department in the country, and is counted among the best globally; according to this year's Shanghai Rankings (now called ARWU Rankings), it occupies the 31st position among all universities in the world.

The Department has contributed to nation building in another significant way which deserves mention: it has and continues to produce alumni who have distinguished themselves in the field. Some have been involved in shaping the activities of major organisations such as DRDO, ISRO, HAL and NAL, while many serve as faculty in the aerospace departments at different IITs and other universities around the world. Some alumni, including Prof Roddam Narasimha, Prof Inder Chopra, and Prof SN Atluri, are considered legends for their outstanding contributions to the establishment and growth of aerospace science and engineering in India and abroad.

Over the years, the research landscape in the Department has changed significantly with more fundamental, interdisciplinary and product-oriented research taking over from applied research. The interdependence of the Department and organisations such as DRDO and ISRO, which are now self-sustaining, has quietly diminished. Its faculty have now moved into newer areas of cutting edge research, such as hypersonics and shockwaves, structural health monitoring, nanostructures, combustion instability etc. It publishes over 80 international journal papers every year, a number on par with aerospace departments in universities like Stanford. Two of its faculty have set up successful startups within IISc. Its MTech students are in high demand in the industry – placement has been 100% in the last five years.

The Platinum Jubilee of the Department is an appropriate moment in its history to celebrate its outstanding achievements, made possible only because of the brilliance and diligence of its extraordinary faculty and students, both past and present. To celebrate this momentous occasion, the Department is organising this two-day event that includes an exhibition, a technical seminar and an awards function to honour its former faculty and several distinguished alumni from all over the world.

The exhibition has been curated by the Archives and Publications Cell (APC). APC has also brought out this special brochure to showcase the evolution of the Department in its 75 years of existence.

S GOPALAKRISHNAN
Chairperson, Department of Aerospace Engineering
IISc, Bangalore

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The birth and evolution of India's first aeronautics department

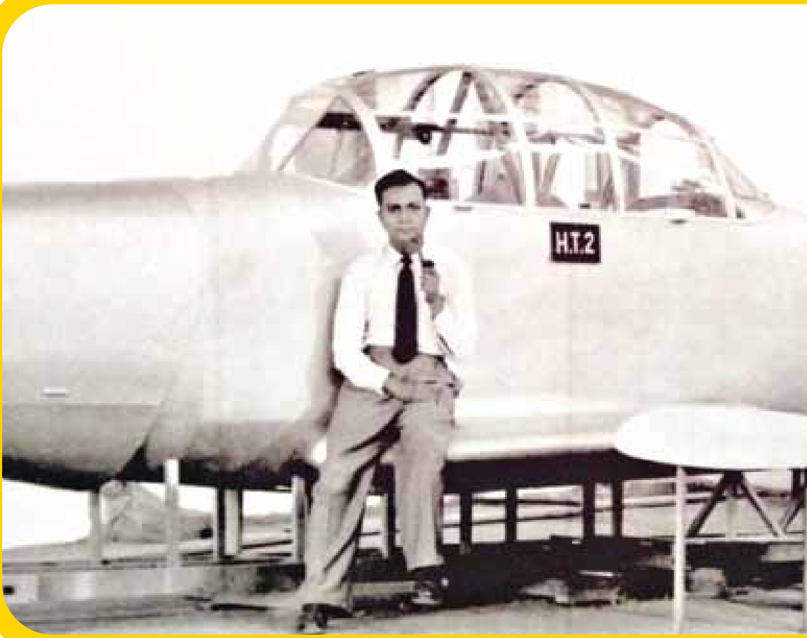
HOW THE DEPARTMENT CAME INTO BEING

Sir M Visvesvaraya

"That in view of the scientific and practical importance of advanced instruction and research in aeronautical engineering and metallurgical sciences and of research in automobile engineering, the Court recommends to the Council that the Government of India, the Provincial governments, the Indian States and the Industrialists be approached for funds which will enable the Institute to equip itself with facilities for such work." This resolution, passed by the Court of IISc in 1941, then presided over by Sir M Visvesvaraya, led to the founding of the Department of Aeronautical Engineering at the Institute in 1942. Its establishment was part of a wave of expansion of engineering departments in the Institute that began under Sir JC Ghosh who served as IISc's Director from 1939 to 1948.

The birth of HAL

The introduction of the new Department coincided with another momentous event in the history of Indian aviation. The industrialist Walchand Hirachand, described by Sardar Patel as a "patriotic industrialist" and one "whose life was a triumph of persistence over adversity," was keen to set up an automobile factory, but wartime exigencies made him change his plans. In 1940, with active encouragement of the Mysore State and 700 acres of land provided by it, he set up Hindustan Aircraft Ltd instead. During this period, this company, which later became the Hindustan Aeronautics Limited (HAL), and the Aeronautical Engineering Department at IISc played a crucial role in the British war effort in Asia. Together, they helped in assembling aircraft, and in the repair and maintenance of aircraft damaged in air attacks. The Institute helped Allied aircraft in other ways too: it provided support for training the technicians of the British Air Force and set up a unit within the Institute campus for the production of hydrogen gas used as a fuel additive. During this period, Hindustan Aircraft also built India's first aircraft, the Harlow PC-5, which was later deployed in the Indian Air Force.



VM Ghatage

Aeronautics Takes Root at IISc

When the Aeronautical Engineering Department, the first such academic department in the country, was set up in IISc, education and research in this field was still in its infancy. In its initial years, the focus was on infrastructure development – designing the building to house the Department and labs, procuring equipment for practical training and planning academic courses. The building was designed and constructed by Otto Koenigsberger, a German who served as Chief Architect of the Mysore State. The Department building, along with a few others that he designed and constructed in the Institute, reflect his minimalistic style, marking a clear break from the ostentatious architecture prevalent in Mysore until then.

In January 1943, course work in the Department started when the first batch of 15 students enrolled in the one-year postgraduate diploma programme. Initially, only students with first-class marks in Mechanical or Electrical Engineering were admitted into the programme which focused on aircraft design and structures. Later additional courses were introduced in several new areas, and students from other disciplines were also admitted. Curriculum for these courses was designed with the help of VM Ghatage, who had a PhD in aerodynamics from Göttingen University, Germany, and was on deputation from HAL. He was assisted in this endeavour by Sir John Higgins, the Chair of the Board of Directors of HAL, WD Pawley, the President of HAL, and LC McCarty, also from HAL.

The Department's close association with HAL was also reflected in a short-term course that was offered specially to the employees of HAL. The association benefited the students too – Pawley, in order to encourage research in aeronautical engineering, offered a scholarship of $3000 for a student to work in the field at any American university for four years. Scholarships were also given to promising students by the Maharaja of Mysore and the Dorab Tata Trust.

This period saw many changes in the academic programmes. The one year Certificate of Proficiency course was converted into a two-year course leading to a Diploma of the Indian Institute of Science (DIISc). After the Institute attained deemed university status in 1958, ME and PhD programmes were also started.

Facilities at the Department

In its early years, though the Department made great strides in imparting education in aeronautical engineering, it lacked the infrastructure to do high quality experimental work. To plug this gap, IISc's first wind tunnel was constructed (built by Koenigsberger and designed by Ghatage) in 1943. This elliptical return circuit wind tunnel measuring 7 ft by 5 ft was built with financial assistance from the Governments of India and Mysore. In this wind tunnel, structural tests, photoelastic and strain gauge tests on scaled models of aircrafts were done, and it was equipped with a balance built at HAL. It initially ran on a Rolls Royce Kestrel Engine because a dedicated high-power engine could not be procured on account of the war.

A decade later, in 1959, a larger 14 ft x 9 ft open circuit wind tunnel was built. Inaugurating this new facility, the then Maharaja of Mysore, Jayachamarajendra Wadiyar said, "The 20th century has brought us instruments to fly with. The puspakavimana of the rishis and kings of our legend is now flying at the behest of the common man." This wind tunnel, which continues to be functional to this day, has been used to test industrial models and even some of the satellite launch vehicle models for their structural strength, aerodynamic design and performance.

In the 1950s, the Aeronautical Engineering Department was headed by Satish Dhawan (who eventually went on to become the Director of the Institute). During his time, he revamped the facilities and courses in the Department. He built the country's first supersonic wind tunnel here. An indigenously designed hypersonic wind tunnel was also built. This national facility was used by other organisations like the ISRO and Defence Research and Development Organisation (DRDO). At the behest of the Defence Ministry, a course in rockets and missiles was started by the

Department in 1968. For many years, Dhawan served both as IISc's Director and the Chairperson of ISRO; this ensured cross-pollination of ideas and technology between the Department and the space organisation. An outcome of this was the birth of the Space Technology Cell in 1982. IISc collaborated extensively not just with ISRO, but also with DRDO and Defence Research and Development Laboratory (DRDL). These collaborations led to the establishment of a Joint Advanced Technology Programme (JATP) in 1983.

The HT-2 military trainer

Practical Training

When the Department was born, Walchand's stepbrother, Lalchand, gifted his personal aircraft to the Department, while HAL presented two aircraft engines to the Department for instructional purposes. A few years later, a Pushpak VT-DWA aircraft was acquired from HAL to impart flying lessons. An airstrip was built in the northern part of the campus; and the Institute also obtained a license to operate the aircraft which was initially flown by trained pilots from HAL. Later the Department appointed a full-time pilot. Though not used anymore, this aircraft, now parked in front of the Department, not just attracts the attention of passers-by, but also inspires a new generation of young men and women to take up aeronautics.

One such young man who was inspired by the sight of an aircraft at close quarters was Roddam Narasimha, who went to become one of India's leading aerospace scientists. In a biographical sketch of Narasimha published in *Current Science*, GS Bhat and KR Sreenivasan write about a visit he made to IISc on Open Day: "He saw [a] Spitfire aircraft of World War II vintage (loaned for the occasion by the Indian Air Force), standing in the quadrangle of the Department of Aeronautical Engineering. It was love at first sight; he was so fascinated by the overall design of the aircraft and the complex technology that made it fly that he decided to study aeronautics after his undergraduate degree."

Aeronautics

to Aerospace

New Aerospace Building

With rapid growth in aeronautics and with research becoming more interdisciplinary in recent years, the Department has evolved to keep pace with the changing times. It began to offer courses in areas such as rocket propulsion, aeroelasticity, fluid mechanics, and turbulence. To reflect the increased scope and diversity of courses and research, in 1982 the Department was renamed the Department of Aerospace Engineering. With new labs being added, the number of faculty and students also grew. To accommodate the additional labs, class rooms and research facilities, the Department has moved into a new building, built in the shape of an aircraft. The Department now also has several new high speed wind tunnels.
As it completes 75 years of existence, the Department continues to remain at the forefront of aerospace research and education in the country.

One of the many high speed wind tunnels in the Department

This article was written by Sowmithri Ranganathan

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How the department and its alumni shaped aviation after Independence

IISc AND AEROSPACE RESEARCH IN INDIA

The Department of Aeronautical Engineering on 15 August 1947. VM Ghatage sits fourth from left. RG Harris, the Head of the Department, sits fourth from right

IISc set up its Department of Aeronautical Engineering in 1942 bang in the middle of World War II. It was the year that the Nazis were to begin acting on their horrific plan for a "Final Solution", and that the Japanese military strengthened its grip over Asia and inched closer to mainland India, invading Burma and the Andaman Islands, and attacking Sri Lanka. It was also the year that the 'Manhattan Project' to develop nuclear weapons solidified, and that the British began bombing German civilians and industrial workers "without restriction", leading to devastating air raids like Operation Millenium and Operation Gomorrah that would go on until the end of the war.

World War II didn't reach the Indian mainland until 1943, when Japanese planes bombed its southern coast and in 1944 attacked Kohima and Imphal. But as a British colony, India had to contribute manpower and resources to the war, and back in 1942, IISc had to direct much of its efforts toward the war too, including training "skilled artisans" such as electricians, machinists and carpenters. Although the war wasn't the stated focus of the Department of Aeronautical Engineering, it was involved in it straight away: it was set up with laboratories and a wind tunnel in which Hindustan Aircraft Limited (HAL, renamed Hindustan Aeronautics Limited in 1961) aircraft models were tested, and practical lessons were imparted in collaboration with HAL and British Royal Air Force (RAF) personnel. Classes began formally in the Department on 1 January 1943 with a compact one-year course populated with 15 graduate students and just two members of faculty: a lecturer and an assistant professor.

That assistant professor was Vishnu Madhav Ghatage, a promising engineer in his early thirties who had trained at the University of Göttingen in Germany under Ludwig Prandtl, a pioneer in the field of aerodynamics (who also taught Theodore von Kármán, another important scientist who would go on to found the Jet Propulsion Laboratory at Caltech). Ghatage had completed his doctoral research in Nazi Germany and left for India in 1936 to teach at university in Pune and Mumbai for a few years before joining HAL, which was set up in Bangalore in 1940.

Ghatage, who joined IISc's Aerospace Department on deputation from HAL in October 1942 (the year HAL was nationalised), was to return to HAL in 1948, and eventually rise to be its General Manager and Managing Director until he retired in 1970. HAL went from overhauling and repairing British and American aeroplanes during the war to making indigenous aircraft, and its close relationship with IISc is one that continues to this day. But IISc's early ties to HAL were the first of several important links that would ensure the Department's continued role in influencing the field of aerospace engineering. And it certainly wasn't the last time that World War II would have something to do with bringing to IISc enormously talented scientists who would go on to build India's aerospace programme.

Burgeoning in Bangalore

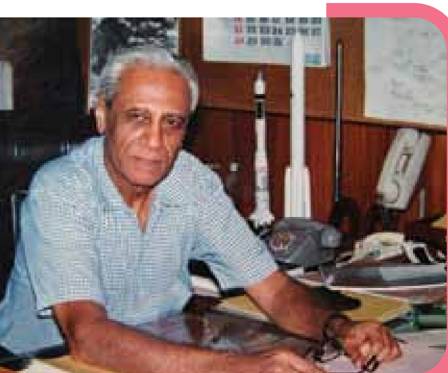
According to IISc records, in April 1946, a Mission from the Ministry of Aircraft Production visited the Department and realised that the Institute could contribute to the aircraft industry, both in terms of research and personnel training. "They [the Mission] have since reported in favour of the location of the industry in Bangalore, partly in view of the existence of this Department," says IISc's Annual Report for that year.

Bangalore would go on to play a significant role in the industry's expansion. In 1960, the National Aeronautical Laboratory (NAL, renamed National Aerospace Laboratories in 1993) relocated from Delhi, where it was set up the year before under the Council of Scientific & Industrial Research (CSIR), to premises in Bangalore. Today, even private aerospace companies like TeamIndus have set up in or moved to Bangalore to benefit from the local industry and its ancillary fields.

The year NAL moved to Bangalore, IISc's Aerospace Department began helping them design and set up a large transonic/supersonic wind tunnel, which could be used to test models of vehicles that could travel close to or faster than the speed of sound. P Nilakantan was NAL's Director from its inception to his untimely death in 1964. He was an IISc alumnus who studied under CV Raman (and was dubbed pleasant but "as stubborn as his teacher" by physicist WH Zacheriasen in a letter to the theoretical physicist Max Born). Having then graduated from Caltech with an MS in 1942, he had also served as a lecturer in the Aerospace Department at IISc from 1944 to 1945, and went on to work for the Civil Aviation Department and the Ministry of Defence before joining NAL.

'The troika'

Srinivas Bhogle, who worked at NAL for over two decades, writes that a report authored by Nilakantan in 1956 recommending R&D in aeronautical engineering may have driven the very establishment of NAL (as well as DRDO's Aeronautical Development Establishment (ADE), set up in Bangalore in 1959, and where APJ Abdul Kalam would begin his career). And according to Bhogle, Nilakantan "sincerely believed that he was India's man of destiny in aeronautics. His passion for this role was all-consuming; he saw himself as the grand architect and mastermind of Indian aeronautics."



Satish Dhawan at ISRO in 1982

Irrespective of what Nilkantan may have believed, he wasn't the sole driving force of Indian aeronautics: Bhogle writes of "the troika of P Nilakantan, VM Ghatage, and Satish Dhawan which worked together on dozens of national aeronautical committees, and virtually wrote the country's aeronautical R&D agenda for the future." Ghatage, Dhawan – who was head of IISc's Aerospace Department and later, Director of the Institute – and Vikram Sarabhai – also an IISc alumnus and the Indian Space Research Organisation's (ISRO) founder – were on NAL's Executive Council.

Roddam Narasimha (centre) with Satish Dhawan (in checked jacket) at the Asian Congress of Fluid Mechanics

SR Valluri and Roddam Narasimha, both alumni of IISc and Caltech, would follow Nilakantan as directors of NAL. Valluri, only 41 when he took charge, would oversee NAL for nearly two decades, through exciting moments as well as a lull that Dhawan reportedly described as being like "a beautiful bride, all decked up, but with nowhere to go." (Incidentally, Valluri married Shyamala Manel, a cousin of Nalini Nirody, who married Dhawan.) By the time he retired in 1984, Valluri had procured approval for the Light Combat Aircraft (LCA) programme and was appointed Director-General of the Aeronautical Development Agency (ADA), the apex body set up in Bangalore that year to manage the programme. Narasimha, a student and then member of faculty at IISc's Aerospace Department for several years, would carry forward the LCA programme at NAL, and initiate several new successes like the FloSolver, a parallel computer for Computational Fluid Dynamics. He was also on HAL's board of directors and was the longest-serving member on the Space Commission, and remains associated with IISc to this day.

The criss-crossing trajectories of the Aerospace Department's faculty and alumni have helped build what its current Chairperson, S Gopalakrishnan, describes as an "ecosystem". From training programs for DRDO scientists to providing IITs with faculty members, Gopalakrishnan says the Department's footprint has been ubiquitous. HAL, NAL, and ISRO are its close relatives.

However, considering the comparatively large role that ISRO plays in the public imagination and the strong connection it would come to have to the Aerospace Department, it is perhaps ironic that the Department had little to do with ISRO's earliest years. There, the seed appears to be World War II: without it, perhaps there may never have been a direct link at all.

Jab Sarabhai met Bhabha

Homi J Bhabha

Circling back to World War II and 1942 brings us to Vikram Sarabhai, a young student from an influential Ahmedabad family, who came to IISc. The war had interrupted his studies at Cambridge, where he had just completed an undergraduate degree in physics and maths, and he had been given permission to continue working towards his PhD while back in India on the condition that it would be supervised by CV Raman. That year, he published the results of his study titled 'Time Distribution of Cosmic Rays'. Amrita Shah, in her book *Vikram Sarabhai: A Life*, points out that his chosen subject of cosmic rays was not a popular one at the time, and suggests that it may have been Raman's influence that set him on that line of inquiry.

The same year, it was at IISc that Sarabhai met Homi J Bhabha, whom Shah describes as "the man who was to found India's atomic energy programme and loom like a Colossus over Indian science until his death in the mid-1960s."

Bhabha had been made Professor at the newly set up Cosmic Ray Research Unit in 1942. Shah emphasises that while Bhabha was interested in cosmic rays for the atomic particles they revealed, Sarabhai would come to see them as tools to study outer space. The friendship between the "two princes of Indian science", as she describes them, was forged over science as well as their shared elite backgrounds and "taste for the good life". This bond would mean a great deal to Sarabhai's career further down the line.

Vikram Sarabhai

When the war ended in 1945, Sarabhai returned to Cambridge to submit his PhD thesis. It was in 1947 that he travelled back to India, and set up the Physical Research Laboratory (PRL) in Ahmedabad. As research at PRL continued alongside Sarabhai's numerous other commitments and interests, he had begun to speak to his colleagues there about beginning a space programme. The Cold War, which began soon after World War II ended, was pushing this new technology forward, and although Sarabhai was not interested in developing weapons, he was keen on developing a rocket programme for research and satellite technology for communications.

Sarabhai
the stargazer

Shah writes that Sarabhai was "very clearly persuaded of an almost paternal role for himself with regard not just to his family but all the people he interacted with, the nation and then humanity as a whole." He dreamed of using space technology for long range weather forecasting, "applications in agriculture, forestry, oceanography, geology, mineral prospecting and cartography", with a "strict focus on peaceful ends". At a time when no developing country could have hoped for a space programme, Sarabhai, gutsy, ambitious and far sighted, worked towards making it a reality.

Vikram and Mrinalini Sarabhai

In 1961, with Bhabha's influence, PRL was recognised as a centre for R&D in space sciences, and Sarabhai became a board member of the Atomic Energy Commission (Bhabha was its Chairman, and in 1966, Sarabhai would succeed him). In 1962, Sarabhai was appointed Chairman of the Indian National Committee for Space Research (INCOSPAR) and began looking for a suitable location for their sounding rocket experiments: they settled on Thumba, a fishing village in Kerala named after a flower. In November 1963, the first sounding rocket was launched from India. Six years later, INCOSPAR grew into ISRO. When Sarabhai died suddenly in 1971 at the age of 52, ISRO, peopled with young and passionate scientists but lacking in a formal structure that would ensure its continuity, would have to change drastically.

S Dhawan

Dhawan's 'new direction'

When Sarabhai passed away in 1971, Dhawan was contacted by Indira Gandhi, who was Prime Minister at the time, and asked to run ISRO. Dhawan happened to be on sabbatical at Caltech, and agreed to the job on two conditions: that he continue as IISc's Director simultaneously, and that ISRO be shifted to Bangalore. Gandhi agreed.

Dhawan was an engineer who had interned at HAL and was mesmerised by aircraft. He received a scholarship in 1945 to study aeronautics in the US and graduated from Caltech. On his return, he joined IISc's Aerospace Department as faculty in 1951, and was made Head of the Department in 1956. He took over as the youngest Director of IISc in January 1963, and by the time he was made ISRO's Head, he had already achieved considerable stature.

In his memoir, *ISRO: A Personal History*, scientist R Aravamudan writes about the day Dhawan first arrived at ISRO in Thumba, and was annoyed by the elaborate reception given to him. It was to signify a huge change in culture: "We were accustomed to Sarabhai's visits which often resembled some kind of endless durbar." Aravamudan goes on to write, "Sarabhai's management style was that of a patriarch dealing with a small well-knit family. [...] There were no formal systems in place, with parallel technical teams operating. Sometimes they would work on the same system without any coordination." Dhawan, who Aravamudan describes as "businesslike", with a "systematic approach" and "no-nonsense style", inherited both Sarabhai's extraordinary vision and successes as well the fledgling organisation's internal mess: "widely dispersed teams" and employee agitations that were to continue for several years, some even turning violent. He brought to ISRO the tight structure it needed to handle the growth that was expected of it. Dhawan also brought IISc's Aerospace Department directly into the picture. Aravamudan writes that he was "very particular that local industry and academia should be associated with the programmes. He felt there should be a two-way dissemination and absorption of expertise. So he inducted organisations like HAL, HMT and BEL and institutions like IISc and government research laboratories to partner ISRO." Aerospace Department alumni like PS Nair, who worked on India's first satellite mission, would go on to leave their mark at ISRO.

K Kasturirangan, ISRO's former Chairperson, said in a talk at the International Centre for Theoretical Sciences (ICTS) earlier this year that Dhawan "transformed every institution he got involved with" and "strengthened and gave new direction to the Indian space program." And in the process, Dhawan appears to have placed the Aerospace Department in the forefront of Indian space technology.

3

The old building at IISc, designed by German architect Otto Koenigsberger, represents an architectural style that blends minimalism and functionality

THE DEPARTMENT'S FIRST HOME

The old Aerospace Engineering building

IISc is over 100 years old with many stories to be told. And not just about its people. There are also tales of its buildings waiting to be recounted. Hidden amidst the lush canopy of the Institute is one such building which until a few years ago was the home of the Department of Aerospace Engineering – called the Department of Aeronautical Engineering until 1982. The building oozes vintage charm: it has a classic entrance with the wide wooden doors, pastel tones on its walls, and a striking wing-shaped overhang sloping over the main entrance. It was designed by Otto Koenigsberger, a German refugee living in Bangalore.

During the 1930s, thousands of Jews fled Germany after the Nazis came to power. One of them was Koenigsberger who first moved to Egypt when he lost his job in his homeland. After spending a few years studying the architecture of ancient Egyptian temples, he arrived in India to become the Chief Architect of the State of Mysore, a position he held from 1939 to 1948. He constructed many structures during this period in Bangalore: the City Bus Terminal at Kalasipalayam, the Krishna Rao Pavilion in Basavanagudi, the Bathing Ghat in Chickpet, the Tuberculosis Sanatorium on the grounds of NIMHANS, and the Victory Hall (now the Jawahar Bal Bhavan) in Cubbon Park. Koenigsberger was also a town planner. He went on to plan cities like Jamshedpur, Faridabad, Bhubaneswar and Sindri. In 1948, Prime Minister Jawaharlal Nehru appointed Koenigsberger as India's first Housing Director to build temporary houses for people from across the border who had become refugees as a result of India's partition.

Otto Koenigsberger at his desk

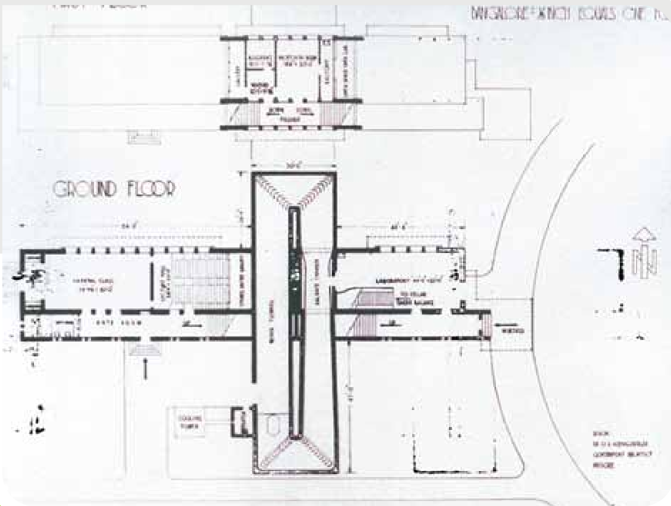
When Koenigsberger was in Bangalore, he became good friends with Homi J Bhabha who was then at IISc. And through Bhabha, he came into contact with the Tatas. They hit it off immediately. This was mainly because they shared an appreciation of the importance of using science in architecture and town planning.

Koenigsberger's association with the Tatas resulted in him leaving behind an impressive architectural footprint in IISc. Besides the Aeronautical Engineering building, he was responsible for the Metallurgy (later renamed Materials Engineering) building, a hydrogen gas plant (now housing commercial establishments including Prakruthi restaurant), and a dining hall and auditorium (currently serving as the Hostel Office).

Trained as a modern architect, he believed in what he referred to as scientific architecture. He saw no contradiction in combining local wisdom with his philosophy of modern architecture. He is described by Rachel Lee, a historian who has studied his work, as an "experimenter". This brought him into conflict with his boss Sir Mirza Ismail, the Dewan of Mysore State, who favoured a more colonial architectural approach. But Koenigsberger persisted with his efforts to incorporate scientific principles into his designs, though he often gave in to the demands of Ismail who insisted on porticos and clock towers. However, he had more freedom to express himself in the buildings he designed as a private architect, including those at IISc. The first of these was the Department of Aeronautical Engineering.

Koenigsberger designed and constructed the building in quick time. He also designed India's first wind tunnel, which is embedded in the building (the tunnel still exists, but has not been used for many years). In 1959, an open-circuit wind tunnel was constructed, one that continues to be used to this day.

In a journal called *Architecture Beyond Europe*, Lee provides a vivid description of this building. She writes: "The most ambitious element of Koenigsberger's design is undoubtedly the 30 m long elliptical low-speed closed-circuit wind tunnel. The wind tunnel loop, which has a test section of 2.2 m x 1.5 m, and a maximum wind speed of about 200 mph, was cast in concrete and partially embedded in the ground. Short granite buttresses provided additional support. Instead of covering the concrete structure, Koenigsberger, no doubt following his own aim of architectural honesty, exposed it. It was India's first closed-circuit wind tunnel, and Koenigsberger considered its construction, in light of the limited resources and technical expertise available, a huge achievement. Indeed, at the time, the Aeronautical Engineering Department at the IISc was the only place in India where facilities existed for training and research, both theoretical and experimental in Aeronautical Engineering."



Koenigsberger's design of the Aeronautical Engineering building

The external walls of the closed-circuit wind tunnel

Lee continues: "Straddling the wind tunnel is the main building of the Aeronautical Engineering Department. In contrast to the monolithic concrete wind tunnel, the Aeronautical Engineering building is built of white-painted plaster-covered bricks on top of a granite plinth. On the narrow east-facing elevation, a cantilevered porch canopy, which is somewhat reminiscent of a wing, marks the main entrance. The elongated rectangular block contains a laboratory, a lecture theatre and a drawing classroom at ground level, with offices for the professor and an assistant situated in rooms directly above the wind tunnel. Koenigsberger relies on passive techniques for ventilating the building. The south-facing access corridor protects the main spaces from solar gain and, because it is slightly lower than the main spaces, allows for ventilators to be fitted at the top of the walls in the teaching spaces. The narrow plan enables effective cross ventilation and the north-facing elevation provides natural light to the main spaces through two blocks of tall recessed window openings protected from glare and rain by thin bands of black-edged chajjas."

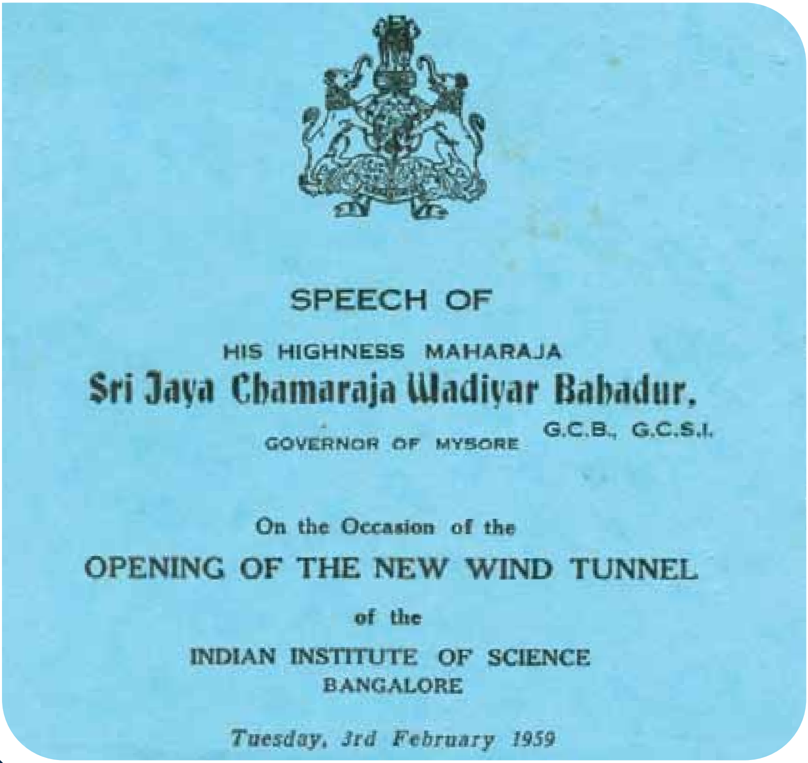
A few years ago, the Department moved to a new, bigger building. But the old one still stands and with it the many stories of its glorious past, including that of its association with an exiled architect who left behind a minimalist modern architectural legacy.

This article was written by Akhila Thomas

The speech of the Maharaja of Mysore at the inauguration of the open-circuit wind tunnel in 1959

4

'I HAVE MUCH PLEASURE IN DECLARING OPEN THE NEW WIND TUNNEL'



SPEECH OF

HIS HIGHNESS MAHARAJA

Sri Jaya Chamaraja Wadiyar Bahadur,

G.C.B., G.C.S.I.

GOVERNOR OF MYSORE

On the Occasion of the

OPENING OF THE NEW WIND TUNNEL

of the

INDIAN INSTITUTE OF SCIENCE

BANGALORE

Tuesday, 3rd February 1959

Jayachamarajendra Wadiyar, the Maharaja of Mysore

Speech of His Highness Maharaja Sri Jaya Chamaraja Wadiyar Bahadur, G.C.B., G.C.S.I., Governor of Mysore, on the Occasion of the Opening of the New Wind Tunnel of the Indian Institute of Science, Bangalore.

Tuesday, 3rd February 1959

DR. BHAGAVANTAM, LADIES AND GENTLEMEN,

I am sure you all realise as well as I do that I am no authority on Wind Tunnels. My presence here to-day is mainly due to the kindly insistence of the Director. I am, however, very glad of this opportunity to express my admiration for the work that is being done in this Institute and my real interest in the increase and expansion of its Departments. I am pleased to see that the expectation of Mr. J. N. Tata, the Founder, is being fulfilled in abundant measure and that the Institute is serving the cause of progress by extension of knowledge as well as its application in practice.

It is the outstanding characteristic of modern civilization to make insatiable demands both on the resources of nature and on the ingenuity of the human mind. In both cases

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the appetite grows with what it feeds on, because the more knowledge we acquire of the forces of nature the more necessity there is for thinking of uses and methods.

Among the most revolutionary developments in modern times has been that of transport. A few decades in the recent past have surpassed many centuries of earlier human history in the achievement of quickness and ease in the movement of man and things. The speed of land travel, which had been more or less constant over thousands of years from the first domestication of the ox and the horse, received unprecedented acceleration in the nineteenth century with the invention of the steam locomotive. On water too the steamship superseded the vessels of oars and sails; and the process of binding the globe together by the lines of communication began and proceeded apace.

Things that appeared to be a fantastic dream when Roger Bacon imagined them seven hundred years ago have all now been added to the conquests of modern civilization. "There shall be rowing without oars, and sailing without sails, carriages which shall roll along with unimagined speed, with no cattle to drag them; instruments to fly with; a little mechanism which shall raise or lower enormous weights, and bridges over rivers, which shall rest neither on piles nor columns."

The twentieth century has brought us "instruments to fly with". The *Pushpaka Vimana* of the rishis and kings of our legends is now flying at the behest of the common man. Human history has entered upon the age of air transport and space travel, and we have already travelled a good way in it.

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The speed of evolution in aircraft design has been quite in proportion to the speed of the aircraft itself. The tremendous pace of development between the first experiments of the Wrights and the missiles that now invade outer space can be easily realised if we compare it with the rate of progress in the case of other vehicles of transport. The simple machinery of push bicycle, for instance, took a quarter of a century, and had to pass through many strange and comic shapes, before assuming a fairly settled pattern.

In the progress of science and technology, improvement and refinement are hardly less important than basic discovery. This has been so in the case of the application of the principles of aerodynamics and in the construction and testing of aircraft for Civil Aviation as well as for Defence purposes. Improvements are constantly being introduced; and every little improvement that has added to economy or efficiency, to safety or to æsthetic appeal, has been the result of patient and devoted research. The use made of the device of the Wind Tunnel is a case in point. It is also an example of human ingenuity in the pursuit of knowledge. The aircraft that is destined to speed through the air is studied and tested through a stationary model subjected to a flow of air of regulated velocity, and amidst favourable conditions of laboratory observation and experiment.

The Indian Institute of Science is a pioneer in the establishment and evolution of Wind Tunnels in our country. It has now embarked on the design and construction of new ones to serve the needs of the latest developments in aircraft the largest of these employing 1,200 horse power and being capable of a wind speed of 250 miles an hour. I congratulate

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the Insitute and the Department of Aeronautical Engineering on their achievements in this field of research.

I am informed by the Director that in this work the Institute has been enjoying the ready and active co-operation of Hindustan Aircraft Ltd. The co-ordination of the efforts of these two important institutions is bound to be of the greatest benefit for the service of the nation and the progress of science.

I have much pleasure in declaring open the new Wind Tunnel.

THE BANGALORE PRESS

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The contribution of a wind tunnel facility, built in 1959, to the nation

THE OPEN-CIRCUIT WIND TUNNEL

The open-circuit wind tunnel in the old Aerospace Engineering building

V Surendranath is a Principal Research Scientist at the Department of Aerospace Engineering. Since he joined the Institute 27 years ago, he has been closely associated with the open-circuit wind tunnel housed in the original home of the Department (the Department now also has a high-speed wind tunnel complex in its new home). Construction of this wind tunnel began in the early 1950s when the Department was headed by OG Tietjens. It was completed under the stewardship of Satish Dhawan in 1959 and inaugurated by the Maharaja of Mysore, Jayachamarajendra Wadiyar, the same year.

In an interview, Surendranath spoke about this facility, its contributions to the growth of aviation in the country, and why he thinks that this old warhorse deserves continued attention.

Could you tell us about your tryst with the Department?

I joined the Department on 4 April 1990. I had taken up two or three jobs before coming here. Once I came to Bangalore, my fascination with the Institute and the renowned Aeronautical Engineering Department [the original name of the Aerospace Engineering Department] only grew because my friend was here at that time and I used to visit him regularly. I have been very fortunate enough to be a part of this Department.

Why do we need wind tunnels?

Wind tunnels help in fine-tuning the design of aircraft, launch vehicles, complex buildings – everything and anything that requires aerodynamic harmony to function perfectly. The designs engineers come up with based on theoretical and empirical equations may not work flawlessly in the real world. Therefore we need these wind tunnels to validate the designs. They are required to show us how efficiently our models work outside the labs, in the real world.

Coming to this particular wind tunnel, could you tell us a little bit about it, including some of the significant objects that have been tested here?

The tunnel has been operational since 1960, working relentlessly for the scientific advancement of the country. This large wind tunnel was conceived by people who I believe were visionaries. The ample size of the tunnel makes the test section large and this helps us to test even big objects.

Here we have tested all sorts of objects: chimneys, cooling towers, factories, launch vehicles, ships, and of course many aircraft. We have also provided our service to the LCA [Light Combat Aircraft], AMCA [Advanced Medium Combat Aircraft], ship development and other flight configurations. This was the country's biggest wind tunnel for many years, and so most of India's requirements were met by this tunnel. Even now, the lion's share of the testing is done here.

Are the objects tested to scale?

Yes, they are tested to scale.

V Surendranath is passionate about the open-circuit wind tunnel at IISc

What are the models typically made of?

Earlier, especially about 50 years ago, all the models were made of wood. But now with the development of materials science, people are also opting to fashion models out of metal and composite materials such as carbon, glass and even paper. But at the end of the day, we are testing external aerodynamics. We are testing shape, not material. Therefore even models made of gold, platinum, wood or charcoal will give us the same result. What matters is the accuracy with which we fabricate the model.

What has been your most satisfying achievement?

One of our landmark achievements was the flight experiments on the LCA, even before the LCA had flown. But I cannot specifically say that these are my achievements because all the tunnel tests have been a group effort. I am happy that I have contributed to the country in some way.

I believe that the fans in the tunnel have a legacy of their own? Could you tell us more about them?

Our fans were originally made of Andaman Padauk [*Ptterocarpus dalbergioides*] wood. It is a special kind of high-quality wood. We have still preserved one or two blades of the old fan made out of this wood.

Many objects and structures continue to be tested at this facility

Each blade, at top speed, can experience about 30-40 tonnes of load. Surprisingly it has witnessed only two accidents in the 57 years since it started functioning. The first was due to fatigue failure, which happens to all mechanical systems over time. The second accident was due to shear failure. The object went through the mesh and hit the blades of the fan. Since it was rather large, it wrecked the fan blades completely. Due to these structural failures we replaced the wooden blades with composite ones under the guidance of my mentor Prof SP Govinda Raju [a retired aerospace engineer from IISc], and these fans have been running to this day.

How much does it cost to maintain this facility?

It is difficult to estimate the expenses accurately as this is a government institution. Salaries have to be paid to the staff and the professors. There is a lot of expenditure on maintenance, owing to the large size and the age of the facility. But we also earn money from the projects that we take up here. A large scale upgrade for this facility which includes replacement of old motors, improvement of the systems and general maintenance would require funding of about Rs 3-5 crore. Due to high maintenance cost and salary outflow, it is difficult to both sustain and upgrade the facility. We are looking for this kind of bulk funding so that this wind tunnel can be raised to the standards of a world-class facility.

How many people work here?

When I joined the Department, the number of staff working here was 11. Right now the official number of staff stands at three. Next year it will be two.

The importance accorded to this facility seems to be diminishing. Do you see a continued role for this facility to serve IISc?

I believe wind tunnels will have an important role even for the next hundred years to come. It should function and it will function. Of late, a new field called computational fluid dynamics is gaining importance, and therefore actual experiments are being sidetracked. But computation of some things is extremely complex, whereas a wind tunnel can generate data in ten minutes. This is worth its weight in gold. In order to achieve accuracy, both theoretical and experimental work have to be blended in the right proportion. This is why I strongly believe that whatever advancements may take over the field of aerodynamic science and research, wind tunnels are irreplaceable and they will survive long.

One must also remember that this facility is not just about producing publications, but also about contributing to various projects of national importance. This facility belongs to the nation as much as it belongs to IISc. Therefore the number of publications that result from a wind tunnel must not be the yardstick to measure its importance. My only wish is that with my retirement, the doors of this facility are not locked. It takes just seconds to put a lock on something, but it takes years to open it back again.

What fascinates you about this wind tunnel?

This facility has earned its place in history, and its legacy will live forever. When I have a small cold, I run to the Health Centre and get the necessary medication. That is for our maintenance. But for the last 50 years, these fans have been working continuously. All we do is apply grease once in a year. We don't even clean the dust on it. This is what fascinates me. When a system runs with this kind of zealous dedication, it is hard not to return the same feeling towards the facility. These fans, they are my babies and I have given them my all. That is the kind of commitment I have towards this facility and it is the kind of commitment that this facility deserves.

This building also has a closed-circuit wind tunnel that has been shut down for several years. Could you shed some light on it?

The closed-circuit wind tunnel was built during the time of World War II by a renowned German architect named Otto Koenigsberger. It was an elliptical section, a standard tunnel – the kind often seen in [scientific] literature. It used to work on a single fan and was an efficient tunnel. However, due to shortage of staff and insufficient funds, it gradually got phased out. But this structure which is of great historical importance now houses the estate office.

This interview was done by Akhila Thomas

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What goes on at the high-speed wind tunnel complex?

TESTING FACILITY FOR THE FAST AND FURIOUS

The High-Speed Wind Tunnel Complex

In 2015, an Italian tiltrotor military aircraft AW609 was on a test flight at high speeds and it crashed a few minutes after taking off, claiming the lives of both its pilots. Investigating the crash, the air-accident investigation agency ANSV pointed out that insufficient wind tunnel testing of the aircraft's new tail configuration caused the accident. But what are wind tunnels and how do they ensure flight safety?

Shockwaves formed in front of a model at high speeds

Wind tunnels are passages where the effects of high-speed air flowing past a scaled-down model of an object are studied. The object be it a race car or bike, an aircraft, a missile, or even a flying dinosaur – experiences aerodynamic forces inside the wind tunnel, mimicking real world conditions. The data obtained from these tests help engineers improve designs, ensuring flight safety while also saving a great deal of money.

"We have to simulate conditions in a wind tunnel which must be geometrically similar to external conditions like total pressure, temperature, velocity, Reynolds number (ratio of inertial forces to viscous forces), Mach number (ratio of velocity of object to velocity of sound) and so on," says B Vasudevan, Principal Research Scientist, Department of Aerospace Engineering, IISc. "Once these conditions are simulated, we perform tests to find out exactly what happens, for example, to a missile moving at high altitudes."

Many missiles travel at supersonic speeds – that is, they travel at speeds ranging from one to five times the speed of sound, which is 344 metres per second at sea level. Hypersonic objects are those that travel even faster, at speeds as high as five to ten times the speed of sound.
To test objects moving at such high speeds, researchers use wind tunnels that can propel air to supersonic or hypersonic speeds. The first such facility in India was established at IISc in the 1950s in the form of the high-speed aerodynamics lab. "We [now] have three supersonic wind tunnels and two hypersonic wind tunnels," says Vasudevan.

The work for India's first hypersonic wind tunnel was begun in the early 1970s by Roddam Narasimha who was then a Professor at IISc, after obtaining a grant from the Government of India. Owing to a dearth of information on construction of hypersonic wind tunnels, as other countries with such facilities were hesitant to share details, the project faced hiccups. Nevertheless, Narasimha and team continued building the wind tunnel. "We were almost close to finishing it when Narasimha left IISc to become director of NAL. Before leaving he handed this part of the work to me," Vasudevan recalls. After more than a year of relentless efforts, they installed a hypersonic wind tunnel with a diameter of 0.3 m in 1984 and in no time they bagged multiple projects. In 2012, Vasudevan and his group constructed another 0.5 m hypersonic wind tunnel.

How Wind Tunnels help

Wind tunnel testing at hypersonic speeds is important because aerodynamic forces behave differently at such speeds and understanding them can prevent mishaps. Apart from the aerodynamic forces, motion at supersonic and hypersonic speeds cause shockwaves that lead to a change in temperature, pressure, and density of air. As an example of an explosion caused due to shockwaves, Vasudevan says that "a supersonic plane called SR71 that took off in 1966, exploded mid-air. They didn't know shockwaves can kill a vehicle." This happens because shockwaves can heat up structures, making them vulnerable to explosions. This can be avoided by using materials that can withstand high temperatures.

A strain gauge balance

Travelling at speeds faster than sound poses another challenge – it can cause disruption in radio communication. Shockwaves can dramatically increase temperatures in front of the plane, blocking radio transmission due to the formation of charged gas, also called plasma. Studying shockwaves and its effects on models of an aircraft or a missile in a wind tunnel, therefore, is essential.

To evaluate the performance of a model, researchers use sophisticated instruments to obtain data, many of which have been developed indigenously at the lab. A strain gauge balance is one such instrument. "A strain gauge balance is a structural element which is fixed to the model being tested. Based on the proportion of the load [aerodynamic forces], it gives us an electrical output," says Vasudevan. "There are only a few agencies in the world which have the capability to design and build such instruments. We design instruments for NAL and other defence centres. We have built instruments for Europeans and Canadians as well."

The hypersonic wind tunnel built in 2012

IISc has taken the road less travelled by constructing instruments and wind tunnels from scratch. "We learned it the hard way," says Vasudevan. "In this process, we have built over 100-150 instruments." The instruments are constructed in-house and can cost more than Rs 1 crore, if imported. Currently, the facility boasts of having about 30 strain gauge balances. In addition to the strain gauge balances, the lab developed the first fibre optic wind tunnel balance to measure load, twenty years ago. "We were perhaps the first in the world to do that," he says.

Although bigger wind tunnels give better results, lack of space on campus prevents the facility from expanding. The Chairperson of the Department of Aerospace Engineering, S Gopalakrishnan, says that the Government of India had expressed interest in setting up a hypersonic wind tunnel at IISc's second campus in Challakere. "The wind tunnel, if approved, could have accommodated a model half the size of the Light Combat Aircraft," he says. But this proposal didn't materialise for various reasons. The government is on the lookout for other locations to set up a large hypersonic wind tunnel.

Collaborations

IISc has collaborated with both DRDO and ISRO. Vasudevan recalls that IISc set up its first hypersonic wind tunnel at roughly the same time that DRDO was developing its Agni missile. "Agni was in its early stages of development, and they [DRDO] wanted to get a lot of experimental design information and performance evaluation," he says. The team has run perhaps 12,000-13,000 experiments for DRDO since then and the association with them stands strong even today.

Through contractors, the high-speed wind tunnel complex team has worked with leading industry players too, like Honeywell, United Technology Corp, Airbus, and Boeing. The most recent project completed was for HCL Technologies. "They approached us as contractors for Airbus. We had to simulate rainstorm and sandstorm in our tunnel testing. This is important in places like Dubai," Vasudevan says. He adds that they have completed over 100 scientific projects for industries and defence labs so far. The high speed wind tunnel complex at IISc also provides services to other defence and industrial labs that do not have the facility.

What does the future hold?

The lion's share of investment in hypersonic flight research goes into the military sector. India, too, is investing in the development of hypersonic missiles. Hypersonic passenger aircraft, meanwhile, may be possible one day, but given the fate of a supersonic passenger jet airliner, Concorde, which first flew in 1969 but stopped operations in 2003 due to difficulties recovering money and environmental issues, there are many hurdles to overcome.

A scaled-down model at the facility

In the recent past, the private sector has begun investing in hypersonic travel. For instance, in 2015, Airbus patented an idea for a hypersonic plane that could travel from Paris to Tokyo in three hours, a journey that today takes 12 hours. They are trying to develop, in collaboration with other countries, two other hypersonic vehicles that aim to travel at six times the speed of sound. Hypersonic wind tunnels will play a crucial role in developing such aircraft and ensuring their safety. Development of spacecraft, too, will rely on wind tunnels to obtain data to model the launch, re-entry, and landing phases.

In recent years, computer simulations using computational fluid dynamics (CFD) has become a widely used tool for performance evaluation. However, says Gopalakrishnan, “for missiles and aircrafts, certification agencies need CFD and wind tunnel data to check for aerodynamic performance. CFD and wind tunnels cannot replace each other.” Wind tunnel testing, therefore, will continue to play an indispensable role in aerospace engineering.

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A pioneering test facility in the country

SHOCK TUNNELS

TEST MORE THAN JUST AIRCRAFT MODELS

The free-piston driven hypersonic shock tunnel

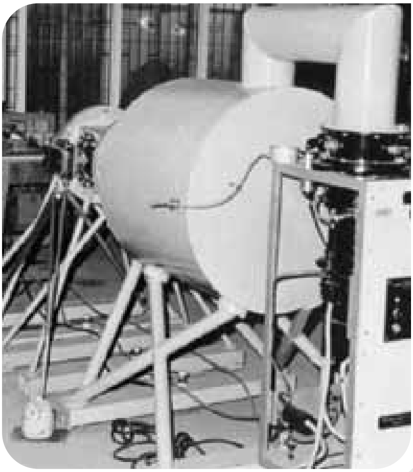
One of the largest shock tunnels in a university setup, India's first hypersonic shock tunnel (HST) was built in 1973 at IISc by NM Reddy, who had studied under Irvine Israel Glass and Satish Dhawan. After holding several positions abroad, Reddy returned to India in 1970 and introduced shock tubes and shock tunnels in India for the first time, a facility which was extensively used for development or testing of ISRO launch vehicles, such as India's first Satellite Launch Vehicle (SLV-3) and Polar Satellite Launch Vehicle (PSLV). Until recently, shock tunnels were predominantly used by space scientists and aeronautical engineers to study heat transfer rates over space vehicles, such as re-entry vehicles, or components such as launch vehicle nose cones and bulbous heat shields. But today, the shock tunnel facility housed in the new Laboratory for Hypersonic and Shock Wave Research (LHSR) has five hypersonic shock tunnels, which are used for different purposes. In this interview, Jagadeesh Gopalan (Professor, Department of Aerospace Engineering) talks about the shock tunnels and how this facility has grown over the years. Here are edited excerpts from the conversation:

IISc got its first hypersonic shock tunnel in the early 1970s. Could you trace its history and growth?

Jagadeesh Gopalan

Professor NM Reddy had just returned to India, and started the High Enthalpy Aerodynamics Laboratory (HEAL) at IISc, which is now known as the Laboratory for Hypersonic and Shock Wave Research. In 1972, he built the first working shock tube. Subsequently, the country's first hypersonic shock tunnel (HST1) was built in 1973, using an aluminium shock tube of 50 mm diameter with a conical nozzle and variable throats capable of producing Mach numbers in the range of 4 to 13.

To give a fair idea, during the 1960s and 70s, a shock tube was the only way by which high temperature, of the order of 4000 Kelvin, could be generated. It was around this time that India began its programme on Satellite Launch Vehicles (SLV) and Agni missiles. So a programme on shock tubes was started at IISc, as a requirement from the space community to measure the surface heat transfer rates in a typical launch vehicle nose cone and SLV model. But it was not enough to just look at heat transfer, and the space scientists wanted to see it in a real vehicle. Gradually, a nozzle was added at the end of the shock tube to create a Mach 6 flow, and that is how it became a shock tunnel.



India's first hypersonic shock tunnel (HST1)

How has the shock tunnel facility expanded since then?

At present, LHSR houses five hypersonic shock tunnels: Hypersonic Shock Tunnel (HST1), Hypersonic Shock Tunnel 2 (HST2), Free Piston Driven Hypersonic Shock Tunnel 3 (HST3), Hypersonic Shock Tunnel 4 (HST4) and Combustion Driven Hypersonic Shock Tunnel (HST5) – all built for different purposes. HST2, made of stainless steel, was built to overcome the limitations on performance capabilities of HST1. Subsequently, in the early 1990s, KPJ Reddy [Professor, Department of Aerospace Engineering] built India's first free-piston driven hypersonic shock tunnel which can operate at very high enthalpy.

Top row: Satellite launch vehicle (SLV) models tested in shock tunnels; Bottom row: Hypersonic vehicle models with different forebody shapes tested in shock tunnels

IISc is home to India's first wind tunnel, an open-circuit wind tunnel, and also the hypersonic shock tunnel. How is a shock tunnel different from a wind tunnel?

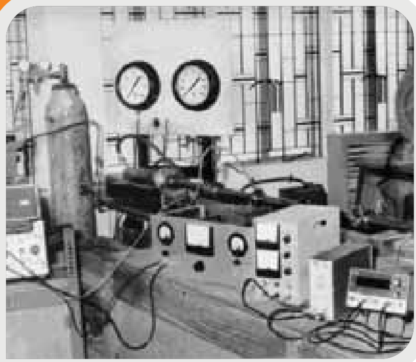
A shock tunnel is an impulse facility which has the ability to produce high stagnation pressures and temperatures, with minimum power requirements and with reduced contaminant of test gas. Essentially, a shock tunnel is a short duration wind tunnel or an extension of a shock tube into a wind tunnel used in the experimental testing of aircraft, wing structures etc., and it is used to generate flows of hypersonic Mach numbers.

In a wind tunnel, the bodies of interest (test vehicles) are kept stationary; an air flow is created which has the same velocity with which the test vehicle is supposed to fly.

The major advantage of using a shock tunnel is that highly energetic flows of high stagnation enthalpy can be generated, which is required to study the features regarding flow around atmospheric re-entry vehicles, ballistic missiles etc. However, the most glaring disadvantage is that all tests have to be performed within milliseconds.

How are shockwaves formed?

Shockwaves are found not only around vehicles which travel at a speed faster than the speed of sound. When there is a massive energy dissipation which takes place in the shortest possible time, shockwaves can be formed naturally. It could be a nuclear explosion, an earthquake, a volcanic eruption, or a massive explosion in the outer galaxy when a new star is born. In fact, when the first nuclear explosion took place, they only saw the radius of the shockwave, which was hundreds of kilometres away. With the radius of the shockwave, we can actually work back and say what the energy [of the explosion] is.



HEAL's first hypersonic shock tube

Apart from shock tunnels, there has also been work at IISc on shock tubes – Satish Dhawan had been working on one. Could you talk about his research and how work on shock tubes progressed from there?

Dhawan was of course a visionary. Along with his former student NM Reddy [who was then working with CG Miller at NASA, and joined the Institute on Dhawan's invitation], he built a small table-top shock tube. But it was not translated into a big shock tube where we could do meaningful measurements for industrial use, and it was not used to measure heat transfer. It was much later that NM Reddy happened to build the first shock tube, in which he was able to test the heat transfer rate on SLV.

Today, we have a hand-held shock tube called the Reddy Tube, named after its inventor Prof KPJ Reddy, which has applications in diverse areas like artificial insemination of cattle, investigating brain injuries due to accidents, removal of brain tumours, water purification and oil extraction, among many others.

Considering that the facility started as a requirement for the space programme in India, what kind of research happens now?

What started out in this department 25 years ago was just for the space application. It was in 2001 that the shockwaves laboratory was established to understand what really happens when shockwaves travel through multiple media. Though numerous applications have sprung up using shockwaves, LHSR predominantly continues to work on aerospace-centric problems because such facilities are invariably required for very high military as well as space applications. But it would not be wrong to say that, over the years, LHSR has also transformed into a hub of interdisciplinary research by bringing together materials scientists, chemists, biologists and industry people to solve many challenging problems in science.

For example, E Arunan [Professor, Inorganic and Physical Chemistry] uses shockwaves as a fundamental tool to understand high-temperature chemical kinetics, and has found out the minimum delay time for burning of jet fuel like JP-10 aviation fuel. This understanding is important because India is building what is called the scramjet engine, a supersonic jet engine.

Similarly, in collaboration with biologists, a first-of-its-kind experiment was conducted in which a micro-shockwave was used to put DNA inside a cell. This device has been patented. It has a few other applications, like putting preservatives in bamboo or removing bio-burden from a natural extract by killing bacteria.

Shockwaves are also finding application in managing chronic diseases. In diabetics, wounds take a long time to heal. A small hand-held device has been developed to reduce this healing time, which has been tested and is undergoing human trials.

In another collaboration with Dipshikha Chakravortty [Professor, Department of Microbiology and Cell Biology], India's first, in fact the world's first, needle-less drug delivery system has been developed.

What lies in the future?

India has not flown any air-breathing engine till now. Though ISRO did some experiments with hydrogen fuel a year back, there is no working system. So the next step is to build a hypersonic flight experiment where the engine development will be done by IISc.

One of our future goals is to build our own scramjet engine and do flight experiments so that India will join the bandwagon of select countries. The BRAHMOS-IISc Centre of Excellence in Hypersonics, to a large extent, will look at the fundamental technology and scientific issues associated with hypersonic flight.

Another jump for us would be the Centre's new building which is expected to be ready before the Department's 75th anniversary celebrations this year.

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A unique Indo-Russian collaborative effort

A CENTRE DEDICATED TO THE JIGSAW PUZZLE OF HYPERSONIC RESEARCH

In 2011, the Indian Institute of Science (IISc) signed an MoU with BrahMos Aerospace to create a new centre for studying an exciting aspect of scientific research in today's world: hypersonic flight. The Centre of Excellence for Hypersonics was inaugurated that year by APJ Abdul Kalam, former President of India and eminent aerospace scientist.

Although research on hypersonics has been conducted in India for the last few decades (particularly at IISc – India's first hypersonic shock tunnel was built here in 1973), there had previously been no major dedicated programmes, says Jagadeesh Gopalan, Professor at IISc's Department of Aerospace Engineering and Chairperson of the Centre. "The Centre came together in 2011 because of Dr Kalam, Prof N Balakrishnan [then IISc's Associate Director], Prof P Balaram [then IISc's Director], and Dr A Sivathanu Pillai [Founder-CEO and Managing Director of BrahMos Aerospace]," he says.

Jagadeesh Gopalan, Chairperson of the Centre of Excellence in High Speed Aerodynamics, with former President of India APJ Abdul Kalam at the inauguration of the Centre in 2011

"We were very clear that there would be no missile development here – our focus would be fundamental science, engineering and technology issues in the broad area of hypersonics research," he adds. The Centre, a separate entity located in the Department of Aerospace Engineering, follows a unique model – young BrahMos scientists are posted here full time, working alongside IISc's faculty and students across multiple departments. Gopalan describes the vision for the Centre as being to complete the "jigsaw puzzle" of hypersonics research, which necessarily combines work from different disciplines. The existing Laboratory for Hypersonic and Shockwave Research (LHSR) at IISc was itself formed in 2010 combining multiple existing laboratories under the Aerospace Department involved in highly interdisciplinary work from materials research to chemical kinetics, and lends much of its expertise to the Centre.

Since it was opened, the Centre has worked successfully on projects worth Rs 35 crore, says Gopalan. He adds that the Centre gives IISc the opportunity to work with industry (which IISc encourages through its faculty entrepreneurship programme – Gopalan himself is the co-founder of a private company), while helping scientists at BrahMos build on their "intellectual capital" through fundamental research on hypersonic flight.

What is hypersonic flight?

The flight of an object can be said to be hypersonic if it occurs at speeds five or six times that of sound or above Mach 5 (sound travels at a speed of 330 m/s. Flight is said to be supersonic if it is faster than the speed of sound). Missiles such as Inter-Continental Ballistic Missiles (ICBMs) and space shuttles can travel at hypersonic speeds, particularly while re-entering Earth's atmosphere. This is associated with high drag and heat transfer, and surface body temperatures can rise up to 6,000 Kelvin. And because the hypersonic regime is dominated by such a large amount of kinetic energy, the atmosphere around such vehicles in flight itself is dissociated – the air breaks down into oxygen and other smaller particles.

Cracking these aspects of hypersonic flight involves incredibly complicated physics that few have managed, but its implications are enormous. For one, as Gopalan points out, "This area is very fertile from an experimental as well strategic point of view for the entire world. It can enhance the capability of the country in terms of deterrent technologies which are required for geopolitical strategies." A hypersonic arms race is currently on, with Russia, China and the US being the main competitors. Missiles travelling at such speeds would be difficult to intercept, and in mid-2017, Russia tested Zircon, its "unstoppable" hypersonic missile system that it claims could make US missile defense systems obsolete. Around the same time, Boeing announced it was planning hypersonic jets in the next two decades for commercial flights that could take premium passengers from New York to Shanghai in two hours.

The 'flying laboratory'

Recreating the conditions around hypersonic flight in order to study them in a laboratory is an enormous challenge. "IISc has made a phenomenal contribution in solving non linear partial differential equations, right from the days of satellite launch vehicles [made by ISRO], computational fluid dynamics exercises in which Dr Kalam was involved right here, right from the time he worked at DRDO," says Gopalan. He adds that it still isn't sufficient to paint an accurate picture with theoretical studies. "Because the atmosphere around the vehicle is dissociated, it is not easily amenable to mathematical treatment."

It is therefore important to experimentally test hypersonic flow. IISc's wind tunnels and shock tunnel facilities can help recreate hypersonic flow conditions in the laboratory. "You keep the body stationary but create an air flow that has the same kind of characteristics as outer space. Because energies are very high, you cannot recreate these for a very long time – just a few seconds. For really high energies like in shockwave research, experimental times are even lesser, like one millisecond," Gopalan points out. The ideal way to conduct hypersonic research would be to have a "flying laboratory", he says, where flight tests could be carried out in order to improve on design. "It might require many flight tests to get info about fundamental physics, like laminar to turbulent flow transitions, which is an important parameter. In India, we have not even begun to do hypersonic flight tests as a mechanism to understand design data.

A view of the Laboratory for Hypersonic and Shockwave Research

"For example if I generate Mach 6 flight [in a wind tunnel] on a generic blunt body which will resemble a flight vehicle, and I get surface heating rates on which I base my design, how good is that data? [I won't know] unless I do a flight test and it survives in actual flight. For us, this is an excellent and exciting opportunity as scientists to be able to do actual experiments so that we can take our numerical data to the next level," says Gopalan.

Solving the jigsaw puzzle

The hard part and the exciting part about working on hypersonics is that the approach to it "can't be segmented", as Gopalan puts it. Every aspect of how a vehicle that travels at hypersonic speed is designed has to be integrated. For one, there's the material used to build the external structure of the vehicle. As it needs to withstand extremely high temperatures, it cannot be made of metal. Ceramic appears to be the best candidate, and work on high temperature ceramics is being done in collaboration with Bikramjit Basu, Professor at the Materials Research Centre one of several instances of how the Centre for Excellence collaborates with students and faculty across disciplines at IISc.

The coating on the surface of a hypersonic vehicle should not make it a catalytic surface at high temperature: an endothermic reaction (one that absorbs energy) would drive the surface temperature even higher. "We had done some very exotic work many years ago on using this phenomenon itself to create an exothermic reaction, so that the shockwave can be pushed away from the vehicle's surface," says Gopalan. Currently, a group led by D Roy Mahapatra, Associate Professor at the Department of Aerospace Engineering, is working on these high temperature resistant thermal coatings.

Hypersonics is dominated by a phenomenon called shockwave, which moves faster than the speed of sound and exerts drag force on the vehicle that it forms around. The region between the body and the wave exists at a very high temperature. Being able to calculate the distance between the body and the wave would help understand how much thermal protection the body would need.

Simply capturing a shockwave on film was a big deal at IISc in the mid 1990s, amidst pioneering work on shockwaves, according to Gopalan. Taking a photograph that would show what a shockwave looked like was a big project, based on a challenge from Kalam. "Prof KPJ Reddy and his team built the first free piston shock tunnel in India, and only about seven countries in the world have such capability," he says.

Another piece of the jigsaw puzzle is aerodynamic design. The wing cross section has to be unique, with a thickness of 1 mm at the leading edge, gradually increasing to 18 mm further. The front portion of the vehicle therefore requires additional lift, and shockwaves can be utilised to provide this. Such design is known as the "waverider". Prof N Balakrishnan at the Department of Aerospace Engineering is working on computational modeling of some of the aerodynamic aspects of such intricate shapes, using computational fluid dynamics (CFD) code called HiFUN, developed indigenously. The waveriders were also tested by the hypersonic wind tunnel team led by Vasudevan, with computations and experiments going hand-in-hand.

Scaled generic hypersonic vehicle configurations

Designs require state-of-the-art Multi Design Optimisation (MDO) tools, and SN Omkar, Chief Research Scientist, and his team are working on advanced MDO tools that can be combined with other computational tools to gain further insights into the hypersonic vehicle design process.

A simultaneous activity at the Centre is the effort to build a supersonic combustion ramjet engine, better known as a scramjet engine.
A scramjet engine uses the shock reflection and the high temperature generated behind it to burn fuel using oxygen present in the air, rather than oxygen carried in a tank. This makes the aircraft lighter. The design of a scramjet engine is unusual to say the least; it looks like a long, narrow, hollow duct, and has no rotating parts. Fuel injected into the engine burns as it goes along and the hot gases produced as a result expand into the engine's diverging cross section, generating the required thrust. A scramjet testing facility was recently built on campus by Swetaprovo Chaudhuri, Assistant Professor at the Department of Aerospace Engineering and his team, right from scratch, and will soon be commissioned. "This is the first such facility in a university in the country where advanced laser flow diagnostics will be integrated to probe the fascinating regimes of combustion of fuels at supersonic speeds," says Gopalan.

Then there's the question of the chemical reactions within the engine, work on which is carried out by KPJ Reddy, Professor at the Department of Aerospace Engineering, in collaboration with E Arunan, Professor at the Department of Inorganic and Physical Chemistry.
A shock tube is used to understand high temperature chemical kinetics – research on it has been going on at IISc since the late 90s. "What is the chemical kinetics associated with such fuel? How do you ensure auto ignition that so it burns immediately in a very short time? How do you ensure it burns completely?" These are the questions they're working to address, says Gopalan.

Guidance and control of the vehicle is another tricky part of their research, aided by Ashwini Ratnoo, Assistant Professor at the Department of Aerospace Engineering. Given the incredibly high speeds at which the vehicle must travel, creating software that updates fast enough to track the vehicle's path and guide it pose a challenge. And the vehicle's sensors need to be able to function at very high temperatures, for which the Centre plans to work with IISc's Department of Electrical Communication Engineering and the Centre for Nano Science and Engineering.

Young scientists

Helping piece together this puzzle at the Centre are eight young scientists with an average age of 27, recruited by BrahMos after completing a BTech or MTech and stationed at IISc. Ragini Mukherjee, who works on structures, Priyamvada KS, who works on guidance and control, and Manoj Kumar K, who works on computational fluid dynamics methodology for hypersonic flows, are among those who work at the Centre full-time, under the guidance of faculty members and in collaboration with other students across departments.

They are in the unusual position of working for industry while being embedded in an academic environment. "We are getting the right training, knowledge and experience here at this age, which we can carry with us wherever we go from here," says Nimesh Thakor, one of the scientists from BrahMos. It isn't quite the same as working towards a PhD at IISc, as their responsibilities don't just lie towards the Centre. "Let me put it this way," says Thakor. "During a PhD you have only one boss. Right now, I have three bosses to answer to," he says while his colleagues chuckle. "Our research has to be application oriented," says Mukherjee, "in a PhD, the academic research you do may not always have that goal."

Gopalan describes the Centre as a "win-win collaboration". It has helped the Institute augment its hypersonic research facilities, such as the new direct connect mode scramjet test facility, small material testing facilities, and is now a hub where ME students have started using tools built for design. At the same time, for Gopalan, the intellectual pursuit remains in the forefront.
A new wing is currently under construction and is scheduled to be inaugurated in November, ahead of the Department's platinum jubilee celebrations later this year.

Interview with fluid dynamicist Rama Govindarajan, an alumnus of the Department

‘THE AEROSPACE DEPARTMENT, LIKE THE WHOLE OF IISc, WAS A QUIETER PLACE THEN’

Rama Govindarajan is a renowned scientist whose work lies in the area of fluid dynamics. The recipient of several awards, in 2007 she received the Shanti Swarup Bhatnagar Prize for her "original contributions to the understanding of instabilities in shear and non-parallel flows, flow entrainment, turbulent transition and small-scale hydraulic jumps." She remains the only woman to have won the prestigious national award for work on fluid dynamics.

Although she originally studied chemical engineering at IIT Delhi and Drexel University in Philadelphia, USA, she made an unusual career choice to begin working in aerospace engineering at NAL, where she continued for a decade while also doing her PhD in aerospace engineering at IISc.

Fifty-four-year-old Govindarajan, who is currently a member of faculty at the International Centre for Theoretical Sciences (ICTS) in Bangalore, has previously worked at the TIFR Centre for Interdisciplinary Sciences in Hyderabad, and the Jawaharlal Nehru Centre for Advanced Scientific Research in Bangalore. Ahead of the Aerospace Department's 75th anniversary, in an interview, she spoke about her interest in the field, her memories of being at IISc, her work, and more. Here are edited excerpts from the conversation:

How did your interest in aerospace engineering begin, and how did that switch from chemical engineering come about?

I came to Bangalore in 1986 because my husband [Sriram Ramaswamy, Professor at IISc's Department of Physics], got a job here at IISc. At that stage I did not actually want to do a PhD; I wanted to work for industry and make something useful – that had been my dream all along. I looked for jobs and went to 37 interviews of various kinds. This direction [aerospace engineering] was the only one that worked out.

I joined ADA in 1987, but in a few months I decided this was not what I wanted to do, I didn't see my talent being used in a rapid way. That's when I contacted Narasimha [Roddam Narasimha, former Professor of Aerospace Engineering at IISc and former Director of NAL], and I moved from ADA to NAL in 1988. I was particular about doing my PhD while working because then I would not have to look for a job at the end of it. NAL gave me the time and computational resources to do my PhD at IISc, which I did as an external registrant from 1991 to 1994.

But it turned out that I did move completely into academics after that.

Govindarajan as a Master's student in 1985

Was working in aerospace a complete departure from what you'd done previously?

I liked fluid dynamics. That was my connection between chemical engineering and aerospace, although the way fluid dynamics is taught and learned and the areas of emphasis are different. Fluid dynamics is a very interdisciplinary field and it wasn't so difficult for me to make that jump. You heard us talking earlier in the lab about singularities: those are questions which appear all the time in aerospace. But those are questions that can actually be asked in chemical engineering, as we found. Later when I became a faculty member, I was able to use both my interests to find new ways to look at problems which originate in chemical engineering, in the petroleum industry, for example, or geophysical flows, which I am looking at right now. A lot of my work now consists of looking at oceans, the atmosphere, clouds, and I wouldn't say it was that big a jump from aircraft boundary layers to this either.

Was there an aspect of working on your PhD that thrilled you in particular? or that defined your time at IISc?

I would say it was the recognition of singularities and seeing how far you can take them.

There is the concept of a boundary layer. If you have an aircraft flowing through wind, you can reverse the problem and say the aircraft is standing still and it's the air that is moving past. The wind some distance away is moving at a constant velocity, which is the negative of the velocity of the airplane. But the wind close to the aircraft is stuck to the aircraft. So it's moving at zero velocity relative to the aircraft. This very thin layer of air, about a centimetre thick, called the boundary layer, determines how much drag there is on the aircraft. If you can zoom it down to a point, that's what you would call a singularity.
If you understand this mathematics well, as well as the math relevant to far thinner layers within the boundary layer, you can write down very simple equations.

I enjoyed that very much. Instead of solving boundary layer equations for stability (in those days they used to run it on a supercomputer, and it used to take two or three weeks to get one answer), because we understood this structure very well, we could minimise those equations, simplify them and I could get an answer on my little desktop in those days within a second, or five seconds. I could get the same answer, or one very close to, the one it would normally take three weeks to find out. This idea was bought from us by Boeing for a small amount of project money.

You come from a prestigious line of scholars in the forefront of boundary layer theory you had the opportunity to learn from Roddam Narasimha, who worked with Satish Dhawan, and like him, worked on his PhD at Caltech. Did that influence your decision to do your postdoc at Caltech? Did being at the famed aerospace department at Caltech, which had been home to other renowned scientists like Hans Liepmann and Anatol Roshko, influence you in any way?

All of us knew about the reputation of Hans Liepmann. He had been a towering figure for us, and it did influence my decision to go there. By the time I reached there, Liepmann would still come in to GALCIT to attend seminars and it was awesome to sit in the same room as him. I worked directly with Professor Anthony Leonard, who is also a very old friend of Professor Narasimha. Professor Leonard's group and Anatol Roshko's group would meet every week and we would discuss things, and Roshko has also been a mentor to me. Definitely, being there influenced my work in a very significant way, because for the first time I could spend time in a department where a lot of people were interested in exactly the kind of problems that I was. I learned about vortex dynamics and nonlinear dynamics during my stay there and that expanded my worldview beyond boundary layers. A lot of my future work depended on what I learned there.

One of my biggest interests now is vortex dynamics, and I look at vortices in clouds, how vortices affect mixing, what vortices do to particles – these are all new dimensions, but the fundamentals were inculcated during that period. That and things like chaotic movement of particles in fluid that was a short project I worked on with Tony Leonard, and that too actually is something I use till this day.

What does your work today involve – is it computational, experimental, or theoretical? What are you working on right now?

Govindarajan at UN Sinha's lab at NAL, circa 2004

My work involves all three. My group does three types of work today: one involves particles in turbulence, or particles in vortical flows. The main thing driving us in this line of work is clouds and how raindrops grow out of them. Clouds are turbulent, they have water vapour, they have aerosol particles, tiny little water droplets suspended in them. Sitting in a super-saturated environment, raindrops could grow due to diffusion. That process should take hours and hours, whereas in a real cloud, big raindrops take between 5 and 15 minutes to form. This is called the 'droplet growth bottleneck' – people don't understand how raindrops can form this fast. There are lots of people who think turbulence is the answer to this, so we didn't come up with it, but we ask specifically how vortex dynamics can influence this process.

In particular, we have shown in a simple model flow that caustics, or regions where raindrops can collide against each other rather than merely coming closer to each other, can contribute to the creation of big drops in a very short time. This work we've done analytically. We take a single vortex, write down simple equations for small water droplets in the vicinity of that vortex, see where they go, see how much they collide into each other to make bigger droplets so those things can be actually written down analytically. In the next step we have done computations in two dimensions where we have a large number of vortices and a large number of raindrops. We're trying to extend this work to three dimensions, to get numerical confirmation of what we're talking about in a situation closer to that in a real cloud.

We do another class of work on fluid structure interactions, where we ask about flexible solids and how they interact with fluid interfaces. We ask how bending, surface tension and hydrodynamics compete with each other to produce some particular dynamics of flexible solids. That is mainly experimental, with a smaller component of theory. We have a very good experimental collaborator, Professor Narayan Menon at the University of Amherst, and the work is carried out in both Amherst and in the KS Krishnan lab at ICTS.

The third kind of question we ask is on flow instability.

A lot of instabilities result in flow going from laminar [orderly] to turbulent [disorderly], so we ask questions about the laminar turbulent transition process in situations where fluid properties such as density and viscosity are a function of space and time. This is directly related to my PhD work on boundary layers, but I now look at these transitions in other scenarios like in oceans, or in industrial flows.

In all these projects, I gratefully acknowledge the huge contributions of fantastic students, postdocs and collaborators.

Since you began working on boundary layer theory in the 1980s, have there been exciting new areas into which the field has branched out today?

The concept of a boundary is not even restricted to fluid dynamics. They can happen wherever there are large gradients of something or the other, in a vast variety of systems, so it need not just be flow next to a wall. In that sense, they can be represented as belonging to a class of singular perturbation problems. Many mathematical features of these singularities have been since worked out, and they have been shown to occur in a range of fluid dynamical problems. In our work, we've found such singular behaviour in pipe flow or channel flow, inside some critical layers. These behaviours actually have their origins in the fact that there is a wall nearby and shear flow close to it. The atmospheric boundary layer is another ballgame. It is studied by a vast number of people now. And for all climate scientists the atmospheric boundary layer is very important.

Even the understanding of the boundary layer over the aircraft wing, which I worked on a long time ago, has undergone a transformation.

What was IISc like when you studied there, and what was the Aerospace Department like?

Different! I would say this is not just for the Aerospace Department but for the whole of IISc, it was a quieter place then. Not every lab was ambitious as they all are today, as I gathered from discussions with my fellow students in different groups and departments. In those days we used to have pockets of excellence, with some labs doing really really well. Now it's more like every lab in every department is doing well. There is a sea change in the level of activity and global connectedness, which makes a huge difference. When I started my PhD, I don't think we had email yet, if I remember right. International travel was harder – so was travel within India. So many faculty and students were far less well-known, especially abroad.

Did you ever get to interact with Satish Dhawan during your studies at IISc? Was access to him easy?

He had already retired by then, but he used to come for seminars and such events, and anyone could go up to him and talk. He was a very nice person. In that sense everybody had access. I never had an elaborate conversation with Satish Dhawan, and that's one of my big regrets. Because I was too shy, basically, to approach him. He'd come for a couple of my talks which I felt very happy about and he would ask questions and we would discuss them. But I wanted to learn a lot more from him which I never did, mainly because I was shy in those days.

Were there any other women in the department at the time?

There was one doing her PhD at the same time as me, and one Master's student.

Even today few women take up engineering of this sort. In electrical engineering or computer science there are a lot more of them. But even in those days, I met several young women who were very crazy about anything to do with aircraft, or spacecraft. They were completely enamoured by this area but unfortunately most of them maybe fell by the wayside…

In what way?

They went into other careers or into no career. It's probably a little easier now but it's still not that easy for women, for a range of reasons.

It was only in 2010 that IISc's Aerospace Department hired its first (and so far, only) female member of faculty. Does it feel strange to hear that, even after all these years?

That's probably also been true of Mechanical Engineering until very recently, or, say, Civil Engineering. It's not just Aerospace. We in science have gotten used to it. We shouldn't be used to it – we shouldn't be happy with it. It is true that there is this leaky pipeline effect. Certainly, a fraction of women who are PhD students don't make it to junior faculty and so on. That's changing a little bit, but not fast enough. Not at all fast enough.

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