CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects. A wind tunnel consists of a closed tubular passage with the object under test mounted in the middle. A powerful fan system moves air past the object; the fan must have straightening vanes to smooth the airflow. The test object is instrumented with a sensitive balance to measure the forces generated by airflow; or, the airflow may have smoke or other substances injected to make the flow lines around the object visible. Full-scale aircraft or vehicles are sometimes tested in large wind tunnels, but these facilities are expensive to operate and some of their functions have been taken over by computer modeling. In addition to vehicles, wind tunnels are used to study the airflow around large structures such as bridges or office buildings.

The framework of literature survey done is shown in Figure 2.1. A brief survey of literature on the history of wind tunnels and the aerodynamic and other studies on wind tunnel were first made and is discussed in section 2.2 and section 2.3. The surveys of different controllers which are used for controlling different non-linear processes including different types of tunnels are discussed in section 2.4.
2.2 HISTORICAL BACKGROUND

Earlier the wind tunnels were used as a means of studying vehicles like airplanes in free flight. The wind tunnel was proposed for reversing the usual phenomena, i.e., instead of the air's standing still and the aircraft moving at speed through it, the same effect could be obtained if the aircraft stood still and the air is made to move at speed over it. In a similar way a stationary observer can study the aircraft while moving, and can measure the aerodynamic forces being imposed on the aircraft.

The study of wind tunnel developed later when the artificial structures like tall buildings became common. The effects of wind on artificial structures or objects needed to be studied when buildings became tall enough to present large surfaces to the wind. This wind forces had to be resisted by the building's internal structure. These forces required to be studied before building codes could specify the required strength of such buildings and such tests continue to be used for large or unusual buildings.

Later on, wind-tunnel testing was applied to automobiles, to determine not only aerodynamic forces but also to the ways to reduce the energy
required to move the vehicle on road. The interaction between the road and the vehicle plays a significant role in these studies. This interaction must be taken into consideration when interpreting the test results. In the real situation the roadway is moving relative to the vehicle but the air is stationary relative to the roadway. The air is moving relative to the roadway, keeping the roadway stationary relative to the test vehicle in the wind tunnel. Some automotive-test wind tunnels have incorporated with moving belts under the test vehicle in an effort to approximate the actual condition.

A whirling arm apparatus was invented by an English military engineer and mathematician Benjamin Robins (1707–1751) to determine drag and did some experiments in aviation theory. Sir George Cayley (1773–1857) also used a whirling arm of 5 feet (1.5 m) length to measure the drag and lift of various airfoils and attained top speeds between 10 and 20 feet per second (3 to 6 m/s).

Anyway, the whirling arm does not produce a reliable flow of air impacting the test shape at a normal incidence. Due to the centrifugal forces and the fact that the object is moving in its own wake, the detailed examination of the airflow is difficult. In 1871 Francis Herbert Wenham (1824–1908), a Council Member of the Aeronautical Society of Great Britain made the invention, design and operation of the first enclosed wind tunnel. A detailed technical data was extracted by the use of this tool.

Osborne Reynolds of the University of Manchester demonstrated that the airflow pattern over a scale model will remain the same for the full-scale vehicle if a certain flow parameter were the same in both cases. This factor is now known as the Reynolds number, which is a basic parameter in the description of all fluid-flow situations, like the shapes of flow patterns, the onset of turbulence and the ease of heat transfer. This forms the central
scientific justification for the use of models in wind tunnels to simulate real-life phenomena. But there are limitations on conditions in which dynamic similarity is based upon the Reynolds number alone.

In 1901, while developing the Wright Flyer, the Wright brothers' used a simple wind tunnel to study the effects of airflow over various shapes. It can be seen that they were simply using the accepted technology of the time, though it was not yet a common technology in America. Subsequent use of wind tunnels proliferated as the science of aerodynamics and the discipline of aeronautical engineering were established and air travel and power were developed.

One of the largest wind tunnels in the world was built at the Washington Navy Yard by the US Navy in 1916 with an inlet of 11 feet (3.4 m) in diameter and the discharge part of 7 feet (2.1 m) in diameter. A 500 hp electric motor drove the paddle type fan blades. Another wind tunnel was designed and built in 1929 in France to test full size aircrafts. It had six large fans driven by high powered electric motors. This wind tunnel continued as the world's largest until World War II.

In 1941 the US constructed one of the largest wind tunnels at that time at Wright Field in Dayton, Ohio. The wind tunnel starts at 45 feet (14 m) and narrows to 20 feet (6.1 m) in diameter. A 40,000 hp electric motor is used to drive two 40-foot (12 m) fans in the wind tunnel. Large scale aircraft models could be tested at air speeds of 400 mph (640 km/h).

The wind tunnel used by German scientists prior to and during World War II is an interesting example of the difficulties associated with extending the useful range of large wind tunnels. Some large natural caves which were increased in size by excavation were, sealed and used to store large volumes
of air which could then be routed through the wind tunnels. This innovative approach made lab research in high-speed regimes and greatly accelerated the rate of advance aeronautical engineering efforts of Germany. By the end of the war, Germany owned at least three different supersonic wind tunnels, with one capable of Mach 4.4 (heated) airflows.

By the end of World War II, the US had built eight new wind tunnels, which includes the largest one in the world at Moffett Field near Sunnyvale, California. It was designed to test full size aircraft at speeds of less than 250 mph. In the vertical wind tunnel at Wright Field, Ohio, the wind stream is upwards for the testing of models in spin situations. The concepts and engineering designs for the first primitive helicopters thus flown in the US.

Later research in airflows near or above the speed of sound used a related approach. High-pressure air was stored in metal pressure chambers, which was then accelerated through a nozzle designed to provide supersonic flow. The observation chamber ("test section") was then placed at the proper location in the throat or nozzle for the desired airspeed.

For limited applications, Computational Fluid Dynamics (CFD) can increase or possibly replace the use of wind tunnels. For instance, the experimental rocket plane SpaceShipOne was designed without any use of wind tunnels. On one test, flight threads were attached to the surface of the wings, which perform a wind tunnel type of test during an actual flight in order to refine the computational model. When there is an external turbulent flow, CFD is not practical due to limitations in present day computing resources. For instance, in the areas of determining the effects of flow on and around structures, terrain, bridges etc, the use of CFD is very complex.
The most effective way to simulative external turbulent flow is through the use of a boundary layer wind tunnel. There are many applications for boundary layer wind tunnel modeling. Understanding the impact of wind on high-rise buildings, bridges, factories etc. can help building designers construct a structure that stands up to wind effects in the most efficient possible manner. Another significant application for boundary layer wind tunnel modeling is for understanding exhaust gas dispersion patterns for laboratories, hospitals and other emitting sources. Assessments of pedestrian comfort and snow drifting are some other examples of boundary layer wind tunnel applications. Wind tunnel modeling is accepted as a method for aiding in Green building design.

Wind tunnel tests in a boundary layer wind tunnel allow for the simulation of the natural drag of the Earth's surface. For accuracy, it is important to simulate the mean wind speed profile and turbulence effects within the atmospheric boundary layer. Most of the standards recognize that wind tunnel testing can produce reliable information for designers, especially for their projects in complex terrain or on exposed sites.

In the USA many wind tunnels have been de-commissioned in the previous 20 years, which includes some historic tunnel facilities. Pressure is brought to bear on remaining wind tunnels also due to high electricity costs, declining or erratic usage and in some cases due to the high value of the real estate upon which the facility sits. But the CFD validation still requires wind-tunnel data. Studies have been done and many are under way to assess future military and commercial wind tunnel needs, the outcome of which remains uncertain. More recently increasing uses of jet-powered, instrumented unmanned vehicles have replaced some of the traditional uses of wind tunnels.
2.3 AERODYNAMIC AND OTHER STUDIES ON WIND TUNNELS

A. Henckels et.al. [1989] described special applications of infra-red imaging for the measurements of the surface temperature distribution on models exposed to a hypersonic flow field. The infra-red thermo vision proves to be a powerful tool to obtain a quick survey of the surface temperature distribution on wind tunnel models. To operate this measurement technique successfully, it is important to adapt the design of the wind tunnel model to the test condition in the tunnel. A method has been developed by A.J.D. Smith et.al [1989] which applies liquid crystal thermograph to the measurement of surface heat flux in short duration hypersonic facilities. A multi-substrate model construction was used, which measures surface heat flux on complex configurations. The technique developed has application over a wide range of model scale, and test times, as demonstrated in the two hypersonic facilities used for these experiments. High values of surface heat flux can be measured without difficulty.

The single failure points (SFP's) in a system is found by either bottom-up or top-down analysis by Owen F. Green [1989]. For a large complex system such, top-down analysis for SFP's is more efficient. The system of interest was high-pressure air heater and its pressure controller of a hypersonic wind tunnel at NASA/Ames Research Center. Over pressurization of heater was the failure effect that occurs. In the analysis, each pressure controller functional failure that could result in heater over pressurization is identified. Existing safety features are then found that prevent the over pressurization. At least one failure in the pressure controller and one or more in the applicable safety features would be required for overpressure to occur. It is therefore necessarily concluded that there are no SFP's for heater over pressurization in this wind tunnel.
A fine-wire thermocouple probe was used by Brian R Hollis' et.al. to determine free stream stagnation temperatures in hypersonic flows [1991]. Tests were made at supply temperatures between 700 and 1900 K and supply pressures between 30 and 1400 atm, with Mach numbers of 14 to 16. Because of its small size and rapid response time, this probe has potential applications in areas of hypersonic research such as boundary layer surveys in limited run-time facilities. Future applications of this probe include wind tunnel wall boundary layer temperature surveys at Mach 18.

G. Simeonides et. al [1991] gave the description of infrared thermograph in a hypersonic blowdown wind tunnel for the acquisition of high quality "two-dimensional" heat transfer data over aerodynamic surfaces. It was shown that the availability of an infrared scanning radiometer and a standard Digital Image Processing (DIP) system in the laboratory may provide the means for the performance of highly efficient heat transfer measurements, which exhibit accuracy levels comparable to those achieved by classical discrete point gauges, like thin film surface thermocouples and resistance thermometers. Infrared thermal mapping was used in measuring heat transfer distributions over complex configurations and in quantifying and locating highly localized hot spots. The results were illustrated by means of a series of examples.

C. Daikert et.al. [1995] measured rotational temperatures of nitric oxide in hypersonic flow by Laser-Induced Fluoresce (LIF) at low densities. The Direct Simulation Monte Carlo method (DSMC) has been applied to study the flow conditions near the surface. The experimental results showed a significant deviation from total accommodation at high surface temperatures. S.A. Chip Stepanek [1995] made studies to characterize and calibrate the free stream flows that result from the nozzle expansion of high temperature gases produced by highly-energetic air heating methods.
The theoretical and experimental results presented by V.I. Alfyorov et.al [1995], relate to flows over such simple bodies as a semishpere, a wedge and a cone investigated in hypersonic wind tunnels of various classes at similar Mach and Reynolds numbers (M=7-8, Re=135-240) and at different air flow velocities. For visualization purposes, an electron beam was used in the first wind tunnel and filming or natural flow was made using neutral and interference light filters in the second and third wind tunnel. Comparison of the calculated and test results shows that the suggested procedure can be an efficient tool to verify and improve the thermo chemical gas models and different flow patterns.

A high Reynolds-number Mach-6 wind-tunnel nozzle for a new quiet flow tube was designed by Steven P. Schneider [2000]. The quiet-flow nozzle was designed to maintain laminar boundary layers on the nozzle walls as far downstream as possible. The nozzle-wall temperature was maintained above the stagnation temperature, near the throat, and is made to decrease to ambient near the exit. This temperature distribution greatly reduces the growth of first and second-mode instabilities.

At hypersonic Mach numbers, the separated boundary layer from the model base develops as a shear layer and separates the outer in-viscid hypersonic flow from low subsonic flow in the base region. S. Pandian et.al [2005] developed fast response sensors and time taken to establish base flow on a typical blunt body was calculated. To gain additional confidence on the base heat transfer distribution, steady pressure measurements were carried out in a conventional hypersonic wind tunnel. The studies showed that for the above test conditions, pressure distribution and the heat transfer on the blunt body base plane is nearly uniform.
A.K. Owen et.al attempted to generate [2007] more reliable hypersonic aerodynamic data on test models in flows closer to the flight test. Wind tunnel experiments have been conducted in two wind tunnel test facilities that enable sting and shroud free model testing. One of the facilities used for hypersonic low Reynolds number testing utilizes a magnetic suspension and balance system. The second facility used for hypersonic high Reynolds number testing utilizes time of flight measurement techniques. Unique state of the art test facilities have been described that can be used for the free-flight testing of models in low and high Reynolds number hypersonic flow.

A brief review of the hypersonic flight vehicle development programs and the existing test facilities in India is given by K.P.J. Reddy [2007]. The existing test facilities are used to develop the preliminary design data needed for flight test as well as for CFD code validation and the large scale ground based tests facilities under construction.

Magneto Hydro Dynamic (MHD) interaction around a conical test body in a hypersonic argon flow [2008] was experimentally investigated by Andrea Cristofolini et.al. The aim was to produce a database to be used for the validation of numerical codes for the analysis and simulation of the magneto fluid dynamics in hypersonic flows. Speeds at Mach 6 were reached. The flow and plasma characteristics were determined in this experiment. A conical test body was placed at the exit of the hypersonic nozzle that yielded an argon flow at a Mach number of 6. The measurement and control applications for wind tunnel testing typically include the wind speed measurement and control, static and dynamic force measurement, pressure profile measurement, and position and motion control for orienting the model with respect to the wind direction.
S.R. Bhoi and G.K. Suryanarayana, predicted the time histories of settling chamber pressure and storage tank pressure [2008] for a given trajectory of the opening of the PRV, as the Variable Mach number Flexible Nozzle throat was changed from Mach 1 to Mach 4 condition and vice versa. The maximum available run time at Mach 4 using various numbers of storage tanks were also studied.

The wind tunnel experiment for simulating the sudden change airflow was introduced by Yang Zhao et.al [2009]. At first, the downburst profile was simulated in the active control wind tunnel, and the measured and analytical results fitted over 90 percents. And then the time history of step airflow was simulated successfully in this wind tunnel. Finally, the variation of structural aerodynamic parameters was observed and collected by the wind tunnel experiment of a high-rise model under the action of the simulated step airflow.

A.V Popov et.al [2010] considered a morphing rectangular finite aspect ratio wing, having a reference airfoil cross-section. Its upper surface was made of a flexible composite material and instrumented with Kulite pressure sensors, and two smart memory alloys actuators. Unsteady pressure signals were recorded and used as feed back in real time control while the morphing wing reproduce various optimized airfoils by changing automatically the two actuators strokes.

### 2.4. LITERATURE SURVEY ON CONTROLLERS

It is difficult to control the Mach number in test section for intermittent wind tunnel because of unpredictable changes in wind tunnel process dynamics and restriction of air storage volume. To overcome the problem, Guijun Zhang et.al.[1997] presented a synthetic approach which combines
adaptive and auto tuning with feed forward control strategy. The experimental results of control of the Mach number in test section and the injector total pressure for the electric wind tunnel of the new 2.4m x 2.1m injector driven transonic wind tunnel demonstrated the effectiveness of the proposed controllers. The adaptive and auto tuning controller solves the contradiction between the set point tracking and the load disturbance rejection and it has excellent performance of set point tracking and load disturbance rejection.

Experimental results of a transonic wind tunnel test by Pamela and Don [1997], demonstrated the use of generalized predictive control for flutter suppression for a wing model in subsonic wind-tunnel. The generalized predictive control algorithm was based on the minimization of a suitable cost function over finite costing and control horizons. An aircraft that incorporates flexibility in its design is likely to require active flutter suppression (AFS) system to remove aero elastic instabilities. Generalized Predictive Control (GPC) is a linear controller that the literature claims can control plants with variable or unknown dead time, and can take into account real plant constraints in real-time.

J. Matsumoto et.al. [2001] developed a PC based pre-programmed controller for a supersonic blowdown wind tunnel with short run time to overcome the shortcomings on a conventional PID controller for a wind tunnel with minimal air storage. The tunnel starts quickly without any overshoot of the pressure while utilizing the existing devices.

The implementation aspects of a PXI-based high-performance versatile instrumentation and motion control system [2006] configured for wind tunnel applications was done by Chaturi Singh et.al at the National Wind Tunnel Facility (NWTF), Indian Institute of Technology (IIT) Kanpur. The system was implemented using virtual instrumentation technique and PXI
architecture which enhance the productivity and lower the cost. Architecture of a versatile mechanism driven by a DC servomotor was presented whereas the model instrumentation and motion control system yaw angle was achieved through bottom turntable rotation. At NWTF-IIT Kanpur, this system is successfully being used for wind configured in free axis mode. The system can also be easily configured to perform other measurement and control functions for bio-medical, robotics, process control and industrial applications.

A computer based controller was developed by F.K. Lu et.al [2008] which was able to start a supersonic wind tunnel very quickly without any overshoot of the stagnation pressure. The control system consists of a multifunction PC board, a pressure transducer and an automatic valve. An ideal valve opening profile for a particular test was developed based on test data and stored in system memory before a test. After several tests, the pressure disturbances in the plenum chamber are typically reduced to one percent of the stagnation pressure.

2.4.1 PI Controller

Eric M Braun et.al. developed a computer based proportional integral control system for supersonic blowdown wind tunnels in LabVIEW environment [2008]. The control algorithm is based on numerically integrating the differential equations used to model a supersonic blowdown wind tunnel in which the proportional and integral control terms were added and tuned in a simulation to determine their appropriate values.

An anti - wind up compensator was used by Li Congying [2008] for designing a non linear PID controller for dealing with input constraints in winged missile control system. The non linear PID controller had better
adaptability and robustness, and it does not need the complicated work of making gain scheduling. The anti-windup non linear PID controller is validated by full trajectory simulation.

Varghese Jacob et. al obtained a lumped parameter mathematical model for high pressure systems of hypersonic wind tunnel for designing a controller for pressure regulation [2009]. A fuzzy controller was added to a classical PID controller to improve robustness and performance.

A. Jadlovska et.al [2009] focused on modeling and control of nonlinear dynamical system Ball & Plate using Matlab/SIMULINK. The closed loop feedback control structure of PID controller was used for the purpose of control. The designed non linear model of the dynamical system was tested and verified on real model Ball and Plate. The functional schematic for nonlinear model was designed in SIMULINK, where as parameters of model, initial conditions, operating point and PID control algorithms were realized in Matlab. The verification on the real model Ball and Plate was satisfying in the case of control into required position. Although applying of PD controller for control of the simulation model showed better result, its usage for control of the real model was insufficient. Modern engineering control methods can be used in future control problem for solving the real models of dynamical systems.

Jun-Jie Gu [2008] analyzed the ideal change in relationship between the error of the control object and the control parameters. The nonlinear functions are presented to form a nonlinear PID controller, whose parameters are tuned in SIMULINK. The nonlinear PID controller is applied to one main stream temperature control system. The simulation results show an improvement in performance for the nonlinear PID controller than traditional linear PID controller.
Among different kind of controllers PID controller is used by about 90% of the industries and robot controls due to its simplicity and effectiveness. Most of the PID controllers are designed by trial and error method. Henry Zhang [2010] suggested that it is desirable to design a PD controller based on the mathematical model. It was designed for motion control in a multiple link robot whose characteristic polynomial is not unique, and its control schemes depend on particular operating conditions. The analysis and simulations of its closed loop dynamics indicates its effectiveness in fast and accurate trajectory tracking. The results can be used in the design of PID controller for other robots in the industrial applications.

Majority of the industrial process are non linear with inherent time delay. The conventional PID is efficient for linear process, since it is a linear controller. It can be applied for a nonlinear process only if the operating range is limited (narrow). Guy Zaidner et.al [2010] suggested a non linear PID method, along with an optional tuning rules and it was implemented in Programmable Logic Controller (PLC).

P. Dostal et.al [2011] presented a continuous-time nonlinear adaptive control of a continuous stirred tank reactor. The control strategy was based on an application of the controller consisting of a linear and nonlinear part. The derivation of static nonlinear part was by inversion and consecutive polynomial approximation of a measured or simulated input-output data. The dynamic linear part is designed based on approximation of nonlinear elements in the control loop. The polynomial approach with the pole assignment method was used in the control design procedure. Testing of the nonlinear model of the CSTR by computer simulation demonstrated the applicability of the presented control strategy and its usefulness in strongly nonlinear regions. The control strategy is also expected to be suitable for other similar technological process.
The poor performance for transient response or steady state response and bad value of performance indices in traditional Proportional Integral Derivative (PID) controller is due to the fixed parameters. But, analysis and design of the nonlinear PID controller is very complicated and difficult in practice. So, Omer Aydogdu and Mehmet Korkmaz [2011] proposed a dynamic PID controller that changes parameters over time according to the error response. Synthesis and analysis of the nonlinear PID controller were carried out and the system showed good performance.

Hong Zhang and Bo Hu [2012] brought forward a kind of nonlinear PID controller aiming at the control problem of generator excitation system. The algorithm is simple and easy to realize since the controller’s proportional, integral and differential values are nonlinear functions of error function. Simulation results show that the generation excitation system designed with this controller is much better than the traditional PID controller.

In the case of a single tank level control system, the control system is intended to maintain the level of liquid in the tank at some predefined value irrespective of changes inflow of tank. Change in inflow or changes in predefined values are treated as disturbances to the process. According to these disturbances, better tuning algorithms to PID controllers was implemented. D.V.L.N. Sastry et.al [2012] approached the non linear PID controller by including the disturbance parameters to conventional PID controller and implemented different non linear PID control algorithms on tank level control System for observing their response with step input.

Sandra I. Pérez-Aguilar [2013] obtained and validated a mathematical model of plasma nitriding vacuum system and designed and implemented a Proportional Derivative control algorithm for pressure control on the nitriding vacuum chamber .The simulations were done in MATLAB SIMULINK. It
demonstrated the possibility of designing a simple and accurate controller, with an appropriate and validated mathematical model of the system.

2.4.2. Fuzzy Controller

Jian Pei [2005] designed a self tuning fuzzy PID logic controller for traction control in business vehicle. The Fuzzy PID controller shows satisfactory results, as the controller effectively prevent excessive slip of drive wheels under typical operation conditions.

C. W. Tao and J. S. Taur [2005] designed, Proportional–Integral–Derivative (PID)-like fuzzy controller which is robust and has reduced complexity, for a plant with fuzzy linear model. The linguistic information of the plant is used to describe the plant model and it is represented as fuzzy set. The robustness between the complexity reduced fuzzy controller and the classical PID controller for a second-order plant with fuzzy linear model was presented in the paper. The PID-like robust fuzzy controller shows good simulation results.

An educational library was presented by Laurent Foulloy et.al [2006] to be used with the MATLAB/SIMULINK package from the Math works company for the design of fuzzy controllers. It has its foundations in a clear representation of the fuzzy interfaces (fuzzification, inference, defuzzification). Mamdani type conventional fuzzy logic controllers including the rule base are presented. The advanced Takagi–Sugeno fuzzy controllers are introduced from the model equivalence principle;

C.L. Lin and T.L. Wang [2007] proposed an integrated fuzzy-logic-based missile side force control mechanism for the interception of ballistic targets in three-dimensional space. Conventional guidance systems alone are
usually incapable of engaging a high-speed target at low-air-density layers. This difficulty is overcome by proposing a fuzzy side force control scheme configured with two additional auxiliary thrusters to generate extra transverse acceleration and thereby to reinforce the performance.

The fuzzy control theory was taken by Wei-Dong Chen and Xing-Wang Yang [2007] to achieve high precision and stability in the measurement and weigh system of packing industry. The fuzzy- PID controller is developed for the complex nonlinear process. It automatically switches between fuzzy algorithm and PID algorithm according to the error. The controller showed improved performance and was successfully used in a packing machine.

I.H. Altas and A.M. Sharaf [2007] presented a straightforward approach for designing fuzzy logic based controllers in Matlab/Simulink environment. The fuzzy rule base construction was made using the time varying values of control error (e) and its change (∆e) mapped on e-∆e space. The simplicity of the proposed approach was shown by designing a fuzzy logic controller (FLC) in Matlab/Simulink environment. The generated FLC block was simulated to control five different systems for validation. From the results obtained it was observed that the FLC gives acceptable performance.

The tracking control of nonlinear systems based on the fuzzy-model-based approach was done by H.K. Lam and L.D. Seneviratne [2008] and it is applied to a two link robot arm. A fuzzy controller was designed to drive the system states of the nonlinear system to follow those of a reference model.

As the continuation of their work in 2007, C.Y. Li and W. X. Jing [2008] applied the fuzzy set-point weighting Proportional–Integral–Derivative (PID) controller in the development of the flight control system. The controller is developed for a two-dimensional differential geometric (DG)
guidance and control system, whose function is to guarantee the achieved angle of attack (AOA) and track the commanded AOA efficiently. The relation between the stability and the output of the fuzzy inference system was studied by introducing a Lyapunov stability criterion. The PID gain was tuned utilizing a genetic algorithm in the simulations which show the full potentiality of the proposed control scheme. It was evident from the results that the designed controller yields a fast-responding and stable system that is robust to parameter variations.

Farhad Aslam and Gagandeep Kaur [2011] compared the influence of different controllers like P, PI, PID and Fuzzy logic controller in a CSTR to control the concentration of ethylene glycol with the help of concentration of ethylene oxide. The concentration control was found better controlled with the addition of fuzzy logic controller instead of PID controller alone.

A fuzzy PID controller for a multi input and multi output paper machine system was developed by Shah Manit Vijay [2011]. Conventional PID controller was used for this process because of the simple structure and robust performance. The fuzzy controller gives better performance than the conventional controllers. The optimal performance of the fuzzy controller can be further increased by the use genetic algorithm for designing the fuzzy membership functions.

Gaurav and Amrit Kaur [2012] made a performance analysis of the conventional PID controller and fuzzy logic controller using Matlab and Simulink for measuring the flow of liquids, which is a critical need in many industrial plants. Comparison of various time domain parameters is done to prove that the fuzzy logic controller has small overshoot and fast response as compared to PID controller.
2.4.3. Backstepping Controller

Ola Harkeg and Torkel Glad [2000] presented the controller based on the backstepping approach to control the automatic pitch attitude for a generic fighter aircraft. The nonlinear model of the fighter aircraft, describing the longitudinal equations of motion in strict feedback form was developed. The controller worked as expected and was robust against the approximations made in the design.

The magnetic levitation system is a nonlinear system which has been subjected to intensive studies to find a suitable control unit. In the dissertation done by Nawrous Ibrahim Mahmoud [2003], the design of a control law for a magnetic levitation system was performed. The results of the design were evaluated in simulations and real-time measurements by testing the tracking performance of the system. Promising simulation results and satisfying validations in real time were obtained.

Shir-Kuan Lin and Chih-Hsing Fang [2004], proposed an adaptive Backstepping controller for tracking the position of a mechanical system driven by an induction motor, which can be extended to work as an adaptive sliding-mode controller. The effectiveness of the Backstepping controller was demonstrated in their experiments, which shows stable and robust performance against parameter variations and external disturbances.

Arbin Ebrahim and Gregory V. Murphy [2005] applied the Backstepping controller design to stabilize an inverted pendulum, mounted on a movable cart, which is a non linear system. The evaluation of the controller based on performance and the impact of the system characteristics on the system stability show that the controller was well suited for the process.
David Maurice Cooper [2005] presented the development of nonlinear tracking control using the Backstepping method for trajectory regulation control. The results of the Backstepping controller is compared with trajectory linearization control and sliding mode control for tracking performance, which shows better performance compared to the other methods.

In order to obtain high performance and good robustness for the flight simulator, Qingwei Wang et.al [2006], presented an adaptive Backstepping controller, which is robust to the load disturbances and parameter uncertainties. Based on experiment test, the model of the flight simulator with parameter uncertainties and load torque disturbances was proposed. Lyapunov stability theorem was used to design the parameter update law and control law. From the simulation results, it is seen that the proposed control scheme using Backstepping approach, can track the position reference signal successfully under parameter uncertainties and load torque disturbance.

Mahsa Rahmanian et.al.[2007] studied a new combination of nonlinear Backstepping controller scheme with on-line fuzzy system for stabilizing and balancing the inverted pendulum in the upright position. The approximation of the unknown non linear function in each design step is done by the fuzzy system and an adaptive fuzzy controller was developed using the Backstepping technique for a class of SISO uncertain nonlinear systems.

A new control methodology, adaptive Backstepping control (ABC), is applied to a linearized model of an Active Magnetic Bearing (AMB) by Silu You [2007]. The aim of the controller was to regulate the deviation of the magnetic bearing from its equilibrium position in the presence of an external disturbance. A combination of recursive Lyapunov controller and adaptive laws forms the adaptive Backstepping control, which was used in two methods. In the first method based on full-state feedback, all three states in
the linearized AMB model (velocity, position, and current) are used to construct the control law. In the second method, Adaptive Observer-based Backstepping Control (AOBC) with only one feedback signal (position) was employed. It was proved that the adaptive Backstepping controlled AMB system is asymptotically stable around the system’s equilibrium point. The effectiveness and robustness of the adaptive Backstepping control method against external disturbances and system parameter variations were verified and it was found fast and stable.

Noor Asyikin [2010] attempted to control a non holonomic mobile robot to track the desired trajectories using Backstepping technique. The simulations performed using Simulink/MATLab showed that the system could track the trajectories. M.S. Merzoug and H. Benalla [2010] presented a novel speed control technique for a permanent magnet synchronous drive based on nonlinear Backstepping technique. It uses the virtual control variable to make the high-order system simple. The final control output was derived step by step through appropriate Lyapunov functions. The simulation results showed that the controller can successfully track the speed reference signal under load torque disturbance rejection and parameter uncertainties.

A novel-function approximator was constructed by Weisheng Chen et.al. [2010], combining a fuzzy-logic system with a Fourier series expansion in order to model unknown periodically disturbed system functions. The dynamic-surface-control approach of the adaptive Backstepping tracking-control scheme is used to solve the problem of “explosion of complexity” in the Backstepping design procedure. The parameter-dependent integral Lyapunov function which is time varying is used to analyze the stability of the closed-loop system. The simulation examples illustrated the effectiveness of the control scheme.
Shao-Cheng Tong et.al [2011] developed an adaptive fuzzy Backstepping Dynamic Surface Control (DSC) approach for a class of multiple-input-multiple-output nonlinear systems with immeasurable states. Fuzzy-logic system was used to approximate the unknown nonlinear functions and a fuzzy state observer was designed to estimate the immeasurable states. An adaptive fuzzy output-feedback Backstepping-control approach was developed by combining adaptive-Backstepping technique and DSC technique. This method not only overcomes the problem of complexity in the Backstepping-design methods but also overcomes the problem of unavailable state measurements.

2.4.4. Cascade Controller

Zsuzsa Preitl et.al [2007] considered the modeling and control of the electric motor in a hybrid vehicle. Cascade speed control solutions consisting of a classical PI+PI cascade control solution was performed. The controller was designed to cope with different requests, such as variation of the reference signal, load disturbances which depend on the transport conditions and parametric disturbances regarding changes in the total mass of the vehicle. Simulations performed using numerical values taken from a real application consisting in a hybrid vehicle prototype, showed satisfactory behavior.

A novel cascade control strategy for temperature control of air handling unit (AHU) in the centralized heating, ventilating and air-conditioning (HVAC) system was done by Chengyi Guo et.al [2007]. Here a neural network is used in the outer loop in the classical control scheme, which overcomes the tedious tuning procedure for the inner and outer loop PID parameters of a classical cascade control system, making the whole control
system be adaptive and robust. This novel cascade control system has been implemented experimentally on a HVAC system. The effectiveness of the proposed algorithm over the classical cascade control system was demonstrated with the help of test results.

Orlando Arrieta et.al [2008] provided an approach for the application of PID controllers within a cascade control system configuration. The tuning of both inner and outer loop controllers are selected based on considerations about the expected operating modes of both controllers. A new approach was also provided for the assimilation of the inner closed-loop transfer function to a suitable form for tuning of the outer controller.

A cascade-control scheme, based on multiple instances of a second-order sliding-mode-control algorithm, was suggested by Pisano A. et.al [2008], which provide accurate tracking performance under large uncertainty about the motor and load parameters for the speed/position control of permanent-magnet (PM) DC motor drives. The proposed scheme was implemented and tested experimentally on a commercial PM DC motor drive to confirm the precise and robust performance and the ease of tuning and implementation.

Kang Jiayu et.al [2009] used the cascade control system for controlling the PH in an Anaerobic Wastewater Treatment System. The control of PH is a difficult link in the anaerobic treatment system due to its nonlinearity and large time-delay. Based on the mathematical model of PH control, a traditional PID control and a cascade control were adopted to carry out simulation. From the simulation results it was inferred that the cascade control is better in terms of stability, response speed and disturbance resistance.
Zengshi Chen et.al [2011] designed a cascade controller with the sliding mode controller as the inner loop and PI controller as the outer loop for a boost converter. The non linear closed loop error dynamics determines the stability analysis and selection of PI gains.

A new automatic tuning method for cascade control systems based on a single closed-loop step test was proposed by Jyh-Cheng Jeng and Ming-Wei Lee [2012], which identifies the required process information with the help of B-spline series expansions for the step responses. The inner and outer PID controllers were tuned using an internal model control (IMC) approach. Enhanced disturbance rejection was done by the secondary controller, and the primary controller was designed, based on an identified process model that accurately accounts for the inner loop dynamics. The effectiveness of the controller was shown by the simulation results.

Josias M. Jesus et.al [2013] presented six different approaches for cascade type control of a fixed bed reactor for the production of phthalic anhydride by oxidation of o-xylene. The disturbance in feed concentration establishes the dynamical problem, which affect the behavior of the system. In the cascade scheme, the primary loops is responsible for controlling the phthalic anhydride exit concentration, while a secondary loop, maintains an optimal temperature profile. The results proved the effectiveness of designing efficient regulatory structures in combination with conventional controller for industries.

2.4.5. Model Reference Controller

Liu X.J. [2004] developed a nonlinear Model Reference Adaptive Controller based on neuro fuzzy networks, since neuro fuzzy networks not only can approximate nonlinear functions with arbitrary accuracy, but are
compact in their supports, and the weights of the network can be readily updated on-line. The performance of the controller was illustrated by examples involving both linear and nonlinear systems.

Wei SU [2007] proposed a model reference tracking based adaptive PID controller with adaptive mechanisms in both feed forward and feedback paths. The output is forced to track the output of a known reference model. The parameter of the PID controller inserted in the feedback path is computed adaptively by eliminating output tracking errors. They used this approach in robot motion control. Here the advantage was that the mathematic description of the robot is not required for implementing this controller.

Yean-Ren Hwang et. al [2008] analyzed the behavior of a vane-type air motor and designed a model reference adaptive control (MRAC) with a fuzzy friction compensation controller. The rotational speed of the air motor is closely related to the compressed air pressure and flow rate, and due to the compressibility of air and the friction in the mechanism, the overall system is nonlinear with dead-zone behavior. Performance of available controllers on the air motor system has large overshoot, slow response and significant fluctuation errors around the setting points. MRAC with fuzzy friction compensation was validated by experimental results considering the effects of dead zone behavior.

State feedback Lyapunov-based design of direct model reference adaptive control (MRAC) for a class of nonlinear systems with input and state delays was developed by Mirkin, B et.al. [2008]. The design procedure is based on the concept of reference trajectories prediction, and on the formulation of an augmented error. A controller parameterization which attempts to anticipate the future states was also proposed.
Yanquig Peng [2008] proposed Model Reference Fuzzy Adaptive PID (MRFA-PID) control for industrial processes to improve the dynamic response, regulation, precision and robustness of the system. The controller consists of two parts, PID controller and fuzzy logic controller. The PID controller was designed for the nominal plant to guarantee the basic requirement on stability and product quality. The fuzzy logic controller improves the system dynamic performance, and robustness of the system. The effectiveness of MRFA-PID control was illustrated by its application in typical industrial processes.

A. Meroufel et.al [2009], presented a theoretical study on model reference adaptive fuzzy logic controller for vector controlled Permanent Magnet Synchronous Motor drive. The direct current, the cascaded speed, the quadrature current and the adaptation mechanism are implemented by the Fuzzy Logic Control System. Expert knowledge of the system is needed for designing the FLC. To make the controller less dependent on the expert knowledge, the fuzzy speed control was augmented by the model. It was followed by error driven fuzzy adaptive mechanism which reduce the influence of parameter variations.

Using the model reference adaptation law, a direct stable controller for nonlinear SISO systems was developed by Mojtaba Ahmadieh Khanesar and Mohammad Teshnehlab [2010]. Combination of adaptive fuzzy system with model reference controller is advantageous because of the flexibility of fuzzy system and tracking performance of the model reference control system.

Zheng Li [2011] described the model reference adaptive fuzzy controller design and its application on automatic gauge control system. Instead of ordinary adaptive mechanism, the reference model is used by the
controller to produce the error of the closed loop control system response and the actual system output for the desired system. The simulation results showed better control performance, with the ability to resist internal and external disturbances than the conventional control system.

Mojtaba Ahmadieh Khanesar et.al [2011] developed a method capable of tracking a reference signal rather than just regulation. A novel indirect model reference fuzzy control approach for nonlinear systems, expressed in the form of a Takagi Sugeno (TS) fuzzy model based on an optimal observer was proposed. Simulation of the proposed method showed its capability of controlling a chaotic system.

A multivariable model reference adaptive control (MRAC) algorithm was developed by S. Enbiya et.al [2011] to maintain the homodynamic variables mean arterial pressure (MAP) and cardiac output (CO) at the normal values by simultaneously administering two drugs; sodium nitro prusside (SNP) and dopamine (DPM). It is a challenging task to use multiple interacting drugs to control both the MAP and CO of patients with different sensitivity to drugs. Computer simulations showed the robustness of the scheme with respect to disturbances and variations in model parameters.

Ayman A. Aly [2012] proposed a new approach to design an adaptive Model Reference -PID control which has the ability to solve the control problem of highly nonlinear systems such as the hydraulic crane. Performance of the Model Reference response was compared with the nonlinear model response and feeding an adaptation signal to the PID control system to eliminate the error in between. The proposed MR-PID control policy provided good performance in terms of rise time and settling time regardless of the nonlinearities.
Fuzzy Logic Controller based Model Reference Adaptive Controller was designed by R. Prakash and R. Anita [2012] which consists of a Fuzzy logic Controller along with conventional Model Reference Adaptive controller. The sum of the output of conventional MRAC and the output of FLC is given as the control input. The FLC-MRAC significantly improved the behavior of the system, by forcing the system to follow the reference model and minimize the error between the model and plant output.

A. Ganesh Ram and S. Abraham Lincoln [2013] proposed a second order model reference tracking based fuzzy adaptive PI (MRFAPI) controller for the conical-tank level process system. The MRFAPI controller is the combination of fuzzy logic and conventional PI controller. The error between reference model and time-varying parameter of the process plant determines the on-line estimation of the controller parameters. The controller was found to produce the appropriate control signals to control the plant in presence of plant nonlinearity, disturbance and measurement noise.

2.5 SUMMARY

The various inferences derived from this literature survey are as follows:

- Wind tunnels are essential for the aerodynamic study of objects.
- It is an emerging technique for aerodynamic study.
- The survey suggested that there are only a few numbers of hypersonic wind tunnels in the world.
Fewer studies are provided on the development of controller for regulating pressure in the settling chamber of the hypersonic wind tunnel.

The survey helped to find out different controllers that can be used for controlling a non-linear plant.