Aerobasics – An Introduction to Aeronautics

8. The Airplane Configuration

S P Govinda Raju

S P Govinda Raju retired as professor from the Department of Aerospace Engineering, Indian Institute of Science in 2003. He is currently active as a consultant in wind tunnel testing and teaches short term courses in aerodynamics and flight mechanics.

The configuration of an airplane is closely related to its mission. In this article we briefly describe the requirements of representative military and civil missions and indicate airplane configurations suitable for these missions. Evaluation of an airplane configuration for performance, stability and control requires a large amount of data about the aerodynamic characteristics of the airplane configuration. Computational methods and wind tunnel tests are currently used for generating this data. Brief descriptions of these methods are included here.

The configuration of an airplane strongly depends on its application. Airplanes can be broadly classified as civil or military. To these categories can be added unmanned aircraft which have both civil and military uses but are significantly different from manned aircraft. Civil airplanes are primarily meant for the transport of cargo and passengers. In addition, relatively small numbers of civil airplanes of special types are used for applications like agricultural spraying and fire fighting. Military airplanes can be broadly subdivided into combat airplanes and transports. A military transport is similar in design to a civil transport. But, a combat airplane is different and performs a complex mission in a hostile environment and will be considered first in some detail.

Keywords
Airplane configurations, combat missions, computational fluid dynamics, wind tunnels, wind tunnel balance.

1. Combat Airplane

The primary purpose of an air force is to achieve air superiority so that an enemy is denied the use of airspace for defensive and offensive purposes. In pursuit of this aim, combat airplanes are used to perform various missions operating from a friendly base station to destroy enemy aircraft in the air and military infrastructure on the ground. After performing their missions, they return to their base station (and thus have to carry fuel for the return journey). They perform these missions in a hostile airspace. The airplanes are monitored by the enemy using ground and airborne radars. The airplanes are potential targets for destructive fire from guns, rockets and guided missiles directed from the ground or enemy aircraft. Thus, apart from excellent performance and maneuverability, a combat airplane must have low observability in relation to radar and heat-seeking missiles. It must also carry smart avionics for navigation and communication. A degree of armor protection against ground fire is desirable and is often incorporated on tactical (short range) fighters. As a final option for use in emergencies, a life saving device in the form of an ejection seat is invariably incorporated on all combat aircraft.

Combat airplanes have to operate in a hostile airspace monitored by the enemy. The combat mission is hidden from the enemy using a configuration with low radar signature and by flying at low attitude.

The ejection seat incorporates complex mechanisms to eject the pilot from a combat airplane flying at any speed up to its maximum and land him safely on the ground. When activated by the pilot, a mechanism within the ejection seat initiates a complex sequence of events. The canopy of the cockpit of the airplane is first ejected or blown away to clear a passage for the seat. The seat with the pilot seated on it is then pushed out of the airplane to a safe distance by using rocket boosters. During this time, the seat is subjected to a blast of wind corresponding to the flight speed of the airplane. The pilot is protected from this wind by various restraining devices on the seat. After reaching a safe distance, a parachute is deployed to safely lower the seat from the flight altitude to the ground.

1.1 ***Military Missions***: Combat airplanes undertake different types of military missions which can be broadly classified as close air support, interception and ground attack.

Close air support missions are flown in support of an army to destroy enemy tanks, ground supply convoys, guns, etc., located relatively nearby (at a distance of the order of 100 km or less). The attacking airplane carries guns, rockets, missiles and bombs and flies at relatively low speeds and altitudes and coordinates its activities with ground troops. Attack helicopters also perform this type of mission.

When enemy aircraft are detected, combat airplanes are sent up to intercept and destroy these by firing guns, short or medium range air-to-air missiles as appropriate. These airplanes can be relatively light, but, must have excellent performance, maneuverability and agility (ability to shift from one maneuver to another quickly and this implies large longitudinal and normal accelerations, the latter often reaching ten times gravity or 10g). The mission duration is relatively short. With the advent of ground to air missiles, this type of mission is losing its importance.

Missions to destroy enemy ground installations deep inside his territory like airfields, factories, and bridges, involve deep penetration (some hundreds of kilometers) into hostile airspace. As an airplane performing this type of mission starts off with a heavy load of bombs and fuel, it has to fly a major part of the mission at a high altitude and at a subsonic speed to conserve fuel. However, flight near the target has to be at a low altitude to avoid detection by the enemy. The mission is supported by precision on-board navigational instruments so that the bombs can often be dropped on the first and only flight over the target. If detected by the enemy, the airplane has to perform offensive or defensive maneuvers using all the performance and maneuverability available and then rush back to the home base. In this phase,

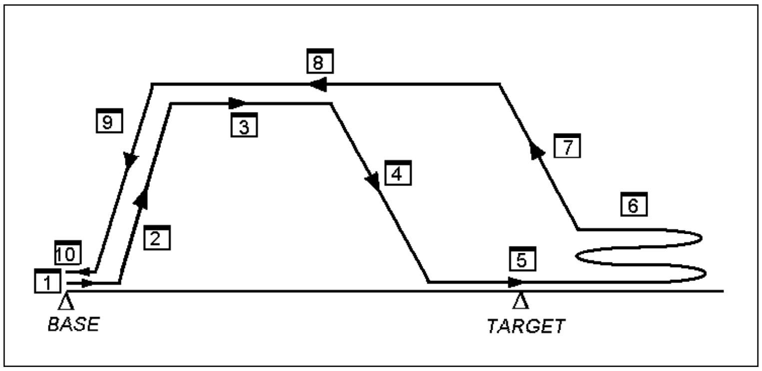


Figure 1. A representative combat mission profile. The airplane with a full load of weapons and fuel takes off from a base [1], climbs to cruise altitude [2] and heads towards the target [3] at an economical cruise speed. At a suitable stage, the airplane descends [4] to a low altitude to avoid detection by enemy radar and continues at a high subsonic speed. When over the target, it drops bombs [5]. If detected and attacked by enemy aircraft at this stage, it performs defensive or offensive maneuvers [6] using its air combat capacity in full. After destroying or escaping enemy aircraft, the airplane climbs to cruise altitude [7] and heads towards the home base [8]. It finally descends [9] and lands [10].

rapid acceleration and flight at supersonic speeds are possible by using the afterburners which are generally fitted to their engines. But this is expensive in terms of fuel consumption and is used sparingly. A typical profile of such a mission is illustrated in *Figure* 1. Advanced countries like USA have operational cruise missiles which also perform some missions of this type.

1.2 ***Combat Airplane Types***: The different types of missions described above cannot all be performed efficiently by one type of airplane. However, combat airplanes are seldom designed for a single mission and the same airplane may be used for different missions by altering the mix of weapons and fuel carried under their wings. The airplanes range from a light combat airplane of about 10 tons take-off weight to a heavy one of up to about 40 tons. A representative combat airplane is shown in *Figure* 2 which illustrates its general features. The configuration uses a long and slender fuselage for minimizing wave drag at flight speeds which can reach Mach 1.5 to 2.0. The wing has a short span (wing aspect ratio of about 3.0 or less) to permit rapid rolls and is very thin (typically 4–5% thick in relation to its chord) to minimize wave drag. The incidence of the wing often reaches large values in subsonic maneuvering flight (generally around 20 degrees but can in special cases reach 90 degrees or more). A tall vertical fin is required to preserve lateral stability at high incidence. The airplane uses one or two engines with a total thrust often

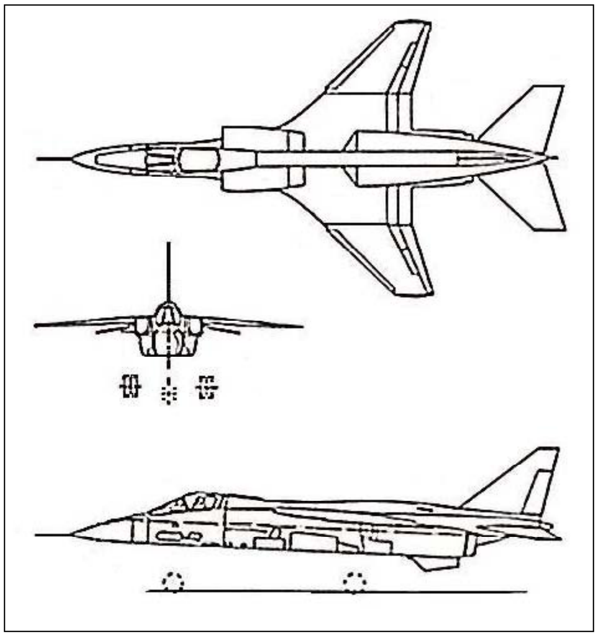


Figure 2. A representative combat airplane. The airplane has a thin wing of large sweep for good supersonic performance. The low aspect ratio wing can roll rapidly for making sharp turns. The powerful and heavy engines are installed within the fuselage close to the longitudinal axis of the airplane. This reduces the roll moment of inertia of the airplane and aids in rapid rolling. External stores (missiles, bombs, rocket pods and extra fuel tanks which can be dropped when empty) are carried below the wings on pylons. (These items are chosen optimally depending on mission specific requirements.)

exceeding the weight of the airplane. This large thrust is required for providing the required level of performance and agility to the airplane.

2. Civil Transport Airplane

Civil aircraft operate under all weather conditions. Economy of operation is of overriding concern. There is only a modest need for maneuverability. Reliability and safety are extremely important as these aircraft often operate up to 50,000 hours during their lifetime extending 30 years or more.

Civil aircraft include small general aviation aircraft meant for private ownership and larger aircraft for scheduled operations. Short-range aircraft, with a range up to ~ 1000 km, and meant for regional operations, are powered by turboprop engines which are capable of speeds up to about 500 km/hr. Larger aircraft meant for long-range operation (up to about 10,000 km) are powered by turbofan engines and cruise at up to 1000 km/hr. The largest of these airplanes, A380 can carry over 700 passengers.

Figure 3 shows a representative civil transport airplane configuration. It has a wing of large span (wing aspect ratio of about 8.8) to minimize induced drag but fairly thick (with a chord-wise thickness ratio of about 15% at the wing root which helps in minimizing wing weight as a thick wing is lighter). The thick wing when combined with a wing sweep of about 28 degrees is suitable for a maximum subsonic speed of about Mach 0.84 which is the limit for this type of airplane. *Table* 1 clearly brings out the differences between a combat airplane and a civil transport.

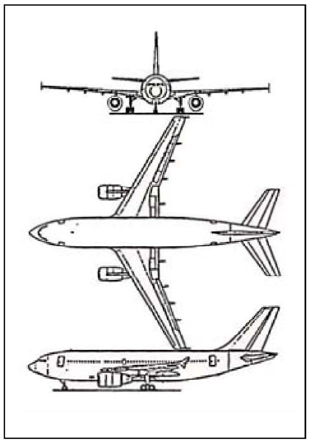


Figure 3. A representative civil jet airplane. The airplane has a thick, high aspect ratio wing with slats and flaps for good performance during take-off and landing. The wing profile and sweep are chosen for cruise efficiency at a Mach number of about 0.8. The large fuselage of circular cross-section is well suited for resisting over-pressure due to cabin pressurization and accommodates a large number of passengers. The engines are carried on pylons under the wing. This helps in reducing wing weight by reducing the bending moment at the wing root due to lift. Further, this layout provides excellent access to the engines for maintenance.

3. Airplane Simulators, Unmanned Airplanes

It is appropriate to mention here the airplane simulator, though it is not an airplane. It is a device primarily used for training pilots on the ground. It simulates the motions of an airplane (all angular motions and limited amounts of linear motions) and the pilot's view from the cockpit dynamically in real time and responds to control inputs by a pilot exactly like the airplane it simulates. Simulators are extensively used for training pilots of both combat and civil aircraft. They are also used in research and development of flight control systems.

A simulator consists of an airplane cockpit complete with all the instruments and controls. It is mounted on a platform which is moved by computer-controlled jacks (generally six in number) simulating the motions of the real airplane. The view from the cockpit of the real airplane is also simulated dynamically. Computer-controlled projectors are used for generating the pilot's view which is projected and viewed on large screens. In response to simulated atmospheric conditions and the pilot's inputs, the computer calculates the motion of the airplane in real time and actuates jacks and projectors to give the same experience to the pilot (feel and view) as flight in a real airplane.

External Dimensions	**Jaguar-A**[1]	**Airbus A 310-300**[2]
Wing span (m)	8.48	44
Overall length (m)	15.52	47
Overall Height (m)	4.92	15.8
Wing area (m^2)	24.18	219
Wing sweep at 0.25 chord	40°	28°
Aspect ratio	3.0	8.8
Weights		
Normal take-off (kg)	10,500	1,50,000
Max take-off (kg)	14,800	1,50,000
Max landing (kg)	8,450	1,23,000
Max external load (kg)	4,450	
Max payload(kg)		32,000
Performance		
Max flight Mach number	1.5	0.84
Radius of action (km)		
Lo-lo-lo mission[3]	835	
Hi-lo-hi mission[4]	1400	
Max range (km)		8000
Power plant		
Thrust (kg)		
Dry	2 × 2340	2 × 23, 600
Reheat	2 × 3350	
Ratio of thrust to aircraft weight (T/W) at normal take-off		
Dry	0.45	0.31
Reheat	0.64	

---

[1] A combat airplane made in UK and France. [2] A civil airplane made by Airbus (Europe) to carry around 220 passengers. [3] The whole combat mission is flown at very low altitude. [4] The mission is mostly at high altitude except near the target.

Table 1. Comparison of representative combat and civil airplanes.

Some missions like surveillance can be done more economically by unmanned airplanes than by manned airplanes. With recent advances in computers, sensors and other avionics, it is now possible to perform some combat functions also, using the unmanned air vehicles (UAVs). The UAVs range from small vehicles weighing a few kilograms all the way to large vehicles up to 10 tons.

4. Airplane Configuration Design and Evaluation

Evaluation of an airplane needs extensive data on the aerodynamic characteristics of the configurations which is at the same time reliable and accurate.

Design of a new airplane typically begins with a preliminary design phase in which a few configurations are evaluated for meeting the mission requirements as indicated by the potential user or by a market survey. The evaluation is based on available data bases and is primarily a computer study which helps in selecting a final configuration for further development. Once the configuration is chosen, the design moves to the next stage where the configuration is thoroughly evaluated for performance, stability and controllability under normal and unusual but safety-critical operating conditions (like one engine failure on a twin engine airplane). Minor modifications are studied and incorporated as required at this stage. This evaluation process needs data on various aerodynamic characteristics of the configuration over a range of operating conditions. These include incidence, sideslip, positions of control surfaces, flaps, slats, air brakes, landing gear (lowered and retracted) and external stores (like drop tanks and bombs). The data is required over a range of flight Mach numbers. An important issue in this context is the accuracy of aerodynamic data. As the accuracy of projections of performance and controllability of the airplane being designed is largely dependent on this, it is imperative that this data must be dependable and accurate. The required accuracy is very high as the customers of airplanes often reject airplanes falling short by only a few percent in performance or other variables.

The aerodynamic data can be obtained primarily from two sources: computations based on basic equations of fluid mechanics and measurements in wind tunnels. Historically, wind tunnels have supplied much of the aerodynamic data. Wind tunnel measurements generally meet the designer's expectations of accuracy. Computational methods are of recent origin and are still evolving. While these methods have been successful in predicting the trends of variations in the aerodynamic data, the absolute accuracy of the data is often open to doubt. The aeronautical industry currently obtains a large part of the design data from wind tunnel testing.

5. Computational Methods

For the flow past a specific body, one may solve the basic equations of fluid dynamics numerically subjected to appropriate boundary conditions, to obtain the solution for the distribution of flow variables (velocity components and stresses) everywhere in the fluid. Forces on the body can then be calculated by integrating the stresses (pressure and skin friction) on the surface of the body. The subject goes by the name of Computational Fluid Dynamics (CFD) which is still evolving. There are many complexities associated with the CFD solutions and they are briefly indicated here.

The basic equations of fluid mechanics are derivable from the relevant conservation laws of mechanics pertaining to mass, momentum and energy. In addition, the properties of the fluid (the equation of state, viscous and thermal properties) need to be given. In the general case, the fluid flow is characterized by the dependent variables (density ρ, pressure p, temperature T and the velocity components u, v and w) which are functions of position (x, y, z) and time t. The conservation laws of mechanics in general result in five nonlinear partial differential equations – one each from conservation of mass and energy and three from conservation of the momentum vector. These together with the equation of state (which is often the perfect gas law, $p = \rho \mathrm{R} T$) complete the set of six equations required for the six dependent variables (ρ, p, T, u, v, w). In addition, the properties of the fluid, namely the viscosity index μ and the heat conductivity K need to be specified.

In a typical case of steady flow past a body, the flow condition far from the body will correspond to uniform flow. The fluid in contact with the body surface is at rest. These boundary conditions have to be imposed on the solution.

A typical CFD solution to the problem as stated above starts by discretizing the domain of flow into a finite number of grid points. The dependent variables are defined at the grid points and relations among them are obtained by applying the conservation laws in discrete form to these variables. The resulting algebraic equations are solved numerically in a computer using various algorithms. From the resulting solution for the variables at the grid points, the quantities of interest like forces on bodies can be calculated by numerical integration.

The accuracy of a numerical solution obviously depends on the number of grid points chosen to represent the domain of flow. It also depends on the flow as characterized by the Mach number M and the Reynolds number R. For very low values of R and M, adequate accuracy can be obtained with relatively small number of grid points. Present-day computers are fully up to this task.

Difficulties are to be expected as one tries to solve the CFD equations at increasing flow Reynolds numbers. The flow in this case has two length scales, one corresponding to the body length L, and the other corresponding to the viscous length scale υ/U which is much smaller. The ratio of length scales is the Reynolds number R, which can reach large values of up to 10^8 in practical solutions. While the number of grid points to represent the flow adequately in the scale of the body may be relatively small, the number of grid points to represent the flow adequately on the viscous length scale will be larger by a factor of R. The fine-scale motion on the viscous length scale is due to turbulent flow and present-day computers cannot handle the number of grid points involved.

In order to obtain useful solutions at practical values of Reynolds and Mach numbers, various approximations are often used in CFD formulations. Inviscid approximations obtained by neglecting viscous effects are useful for analyzing flows past streamlined bodies and thin wings at various Mach numbers. CFD codes based on these methods are called Euler codes as the inviscid momentum equations are generally known as the Euler equations. Viscous CFD codes based on partial elimination of fine scale viscous motions by modeling turbulence using various averaging techniques go by the name of Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES) codes. The name Direct Numerical Simulation (DNS) applies to the codes retaining fine-scale motions. Many practical problems are solved by the RANS codes. DNS is still not applicable to practical problems.

There are many complexities associated with CFD. The final goal of accurately predicting within a reasonable time and effort the aerodynamic characteristics of a complex configuration at all Reynolds and Mach numbers has not been achieved.

While the DNS codes are technically perfect, they are not usable for solving practical problems at the current time due to limitations imposed by current computers. RANS and Euler codes are in extensive use. However, the results obtained using these codes are not universally accurate over all Reynolds and Mach number ranges.

6. Wind Tunnel Tests

A wind tunnel is a device for simulating the flow around a configuration corresponding to flight in the atmosphere. The atmosphere is virtually infinite in relation to the size of the airplane. To simulate this flow, a model of the airplane has to be tested in a uniform stream of air of cross-section very large compared to the size of the model and at the same Reynolds number and Mach number as in flight. In a small wind tunnel, the walls of the tunnel influence the measurement. This influence is called the blockage effect and must be made acceptably small by using a wind tunnel of sufficient size. Wind tunnels to meet the above requirements are very large and complex.

To operate them, a large amount of power reaching up to about 100 MW is required. More than one wind tunnel is often required to cover the full range of parameters – particularly the Mach number. Low speed wind tunnels operate at Mach numbers below about 0.3. A few low speed wind tunnels as large as 20m x 30m in test section exist in some western countries. Wind tunnels for higher Mach numbers are much smaller due to economic reasons. Recently, successful attempts have been made in achieving the required Reynolds and Mach numbers in smaller wind tunnels using pressurized air cooled to low temperatures using liquid nitrogen. Cooling and pressurization reduce the kinematic viscosity of air and hence result in a much higher Reynolds number for the same test section size. We shall only consider low speed wind tunnels running at atmospheric pressure in some detail here.

Wind tunnels to simulate the full scale Reynolds and Mach numbers are large, complex and expensive.

7. Low Speed Wind Tunnels

Figure 4 shows the layout of a typical low speed wind tunnel of the closed circuit type. In this type of tunnel, the air is circulated inside a circuit isolated from the outside atmosphere. Thus disturbances in the atmosphere and weather conditions do not affect the flow in the tunnel and it is possible to obtain very accurate measurements. The test section is a region of uniform flow in which a test model is introduced and studied.

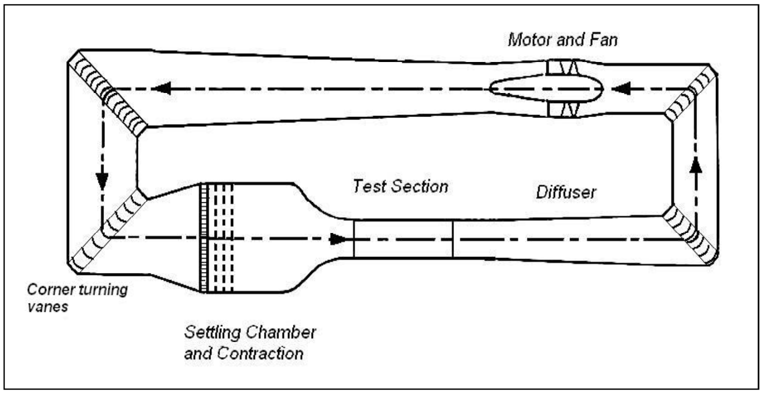


Figure 4. A typical low speed wind tunnel. A wind tunnel creates in the test section a uniform stream of air with a minimum of turbulent fluctuations suitable for testing airplane models. The wire screens, the settling chamber and the contraction help in this. The flow speed and the test section size determine the test Reynolds numbers which must be as close to the flight Reynolds number as possible. The power required to run the tunnel is minimized by reducing flow losses using a diffuser followed by the return circuit of large cross-section.

The tunnel circuit includes a contraction ahead of the test section to accelerate the flow to the test speed. After flowing past the body in the test section, the high velocity air is slowed down in a diffuser before circulating it back using a fan. This reduces the flow losses and permits the tunnel to operate with less power. The honey comb and screens at the beginning of the contraction are helpful in reducing flow disturbances and thus make the flow in the test section more uniform and free of turbulence. Model studies are thus conducted in a uniform and turbulence-free flow. The fan creates the pressure difference required to drive the flow against the flow losses in various sections of the tunnel circuit. There is also a cooler in the circuit to prevent the build-up of heat in the tunnel which is generated by conversion of mechanical energy into heat due to flow losses.

8. Applications of Wind Tunnels

Wind tunnels are useful for qualitative studies involving flow visualization as well as for quantitative studies involving pressure and force measurements.

A simple method of flow visualization is by the use of tufts attached to the surface of the model. A tuft is a short length of fiber with one of its ends glued to the model surface and is free at the other. It aligns with the flow direction in a smooth flow. In regions of separated flow, the tuft oscillates violently. Thus regions of separated flow can be quickly identified and corrective measures (in the form of slightly altered body shapes using fillets) can be applied if required.

Tuft studies only indicate the nature of flow near the body surface. Flow streamlines in the field of flow are rendered visible by injecting ‘smoke’ at a suitable location ahead of the body. The smoke is generally an aerosol consisting of fine liquid droplets of paraffin oil suspended in air. It is produced by condensing paraffin

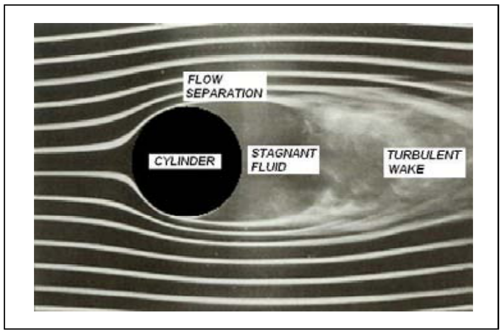


Figure 5. Flow visualization in a wind tunnel: Smoke (an aerosol consisting of fine droplets of a liquid in air) is injected at a suitable location upstream of the model without disturbing the flow. The smoke follows the streamlines and reveals the pattern of flow around the body. This technique is useful as a diagnostic tool for understanding and correcting flow problems.

vapor, produced by boiling, in a moving stream of air. The resulting smoke is introduced into the wind tunnel at several points carefully without producing disturbances. The smoke follows the streamlines of flow and can be observed by using directional lighting which illuminates the smoke but not the surroundings. *Figure* 5 shows a typical picture obtained during a wind tunnel study using smoke.

Distribution of pressure on a body surface is often required in support of structural design activities of airplanes and their components. This is usually obtained by connecting small holes drilled on the body surface to pressure-measuring instruments (pressure transducers) by tubes.

Measurement of forces and moments on airplane configuration and related parts (like stores) constitute a major activity in wind tunnels. The models for these measurements have to be light and very precise and are generally molded in fiber reinforced plastic for use in low speed wind tunnels. Models for high speed wind tunnels are machined in an aluminum alloy using computer-controlled machines. For measurement of forces and moments on the model, it is mounted in a wind tunnel on a balance supported on a pitch-yaw mechanism and is described below.

9. Wind Tunnel Balance

The wind tunnel force measurement system consists of

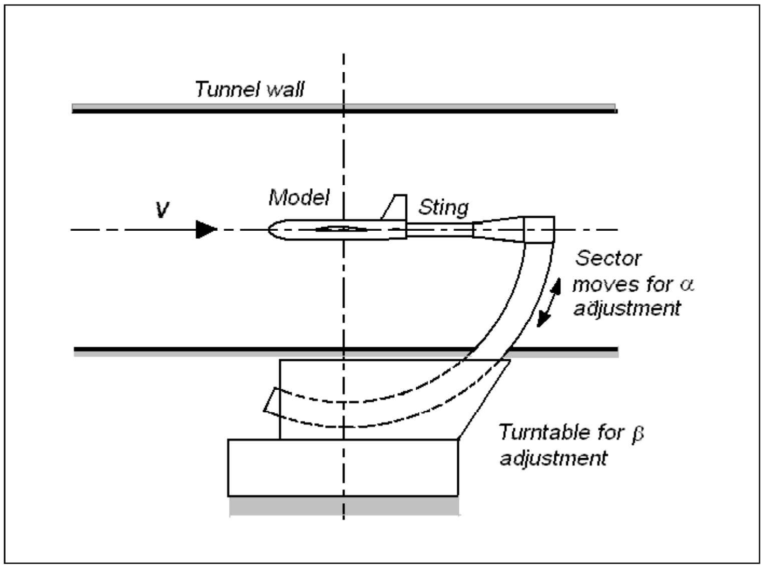
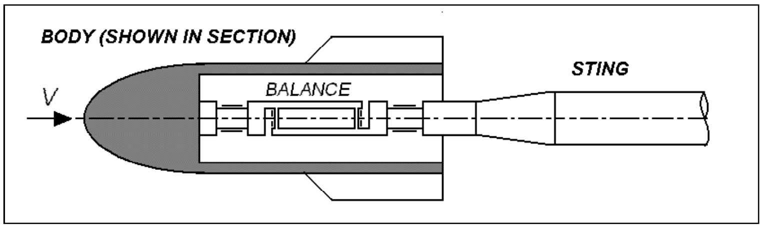


Figure 6. A typical model mounting system. The model of an airplane needs to be tested over a range of incidence and side slip angles. As the wind direction is fixed, any required test condition is obtained by rotating the model about two axes. The sector can be rotated about a horizontal axis passing through the centre of the test section to vary incidence. The turntable at the bottom permits rotation about a vertical axis passing through the centre of the test section to vary the side slip angle. The force measuring unit, the balance, is carried within the hollow model.

a mechanism for rigidly positioning a model of the airplane under study in the test section at any desired orientation (incidence and sideslip) relative to wind direction. This mechanism, shown in *Figure* 6, carries a sting at the end of which is a force measurement device (the balance) on which the model is mounted. The aerodynamic forces on the model are thus transmitted to the sting though the balance as in *Figure* 7.

Figure 7. A typical model set-up for force measurements. The model is rigidly fixed to one end of the balance. The other end of the balance is rigidly attached to the sting which is a part of the model mounting system. Thus, the aerodynamic forces acting on the model are transmitted to the sting through the balance. The balance thus experiences strains due to the aerodynamic forces on the model. The balance is provided with strain gages at suitable locations. Strains are measured at these locations (by an electrical measurement system) and the aerodynamic forces are calculated using the measured strains. Six strain measurements are required for calculating the three forces and three moments due to aerodynamic forces on the model.



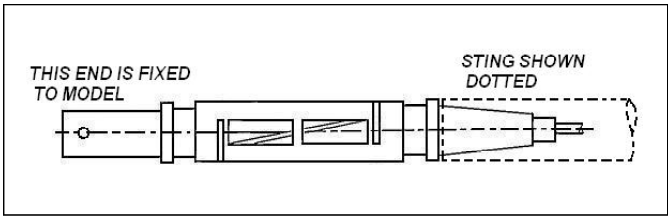


Figure 8. A typical strain gage type wind tunnel balance. The balance is a precisely shaped piece of high strength steel. It is so designed that strain sensing elements at specific locations on it are primarily sensitive to only one of the forces/moments being measured. This helps in enhancing the accuracy of measurements. As any deflection of the balance due to aerodynamic forces changes the model orientation relative to the wind direction, it must be made very small by a careful choice of the balance configuration. Choice of steel as the material for the balance also helps in meeting this requirement.

Figure 8 shows a schematic sketch of a common type six-component balance. The balance consists of an accurately machined piece of steel which is so shaped that strains at specific sections of the balance are very sensitive to specific forces or moments acting on the balance while remaining comparatively insensitive to others. Strain-sensing elements (usually electrical resistance type strain gages) at these locations respond to loads on the balance and an electrical measurement system is used for recording the strains. When in use, one end of the balance (the model end) is rigidly fixed to the model while the other end (the sting end) is rigidly fixed to the sting. During a wind tunnel run, the balance produces six electrical outputs which are linearly related to the six aerodynamic forces/moments acting on the model. The balance is so calibrated that it measures the six force/moment components relative an axis system fixed to the balance with its origin at the geometric centre of the balance. The principle of operation of such a balance is illustrated in *Box* 1.

The balance is calibrated by applying known forces and moments relative to the balance centre by using a calibration rig. A calibration body is mounted on the 'model' end of the balance and loaded by suitable dead weights and levers. The balance sensitivity matrix is obtained as a linear relation between the applied forces/ moments and the response (electrical output in volts) as:

$$\{\mathrm{R}\} = [\mathrm{C}]\{\mathrm{F}\} \quad . \qquad (1)$$

Box 1. Illustration of the Concept of Strain Gage Type Balance

Figure A illustrates the principle of a strain gage type balance for measuring two forces and a moment in one plane. This balance consists of a bar of uniform thickness cut to the shape shown in *Figure* A(i). The bar is of reduced sections at A and B and incorporates a cut-out in the middle leaving only thin vertical connections between the top and bottom parts of the bar. When such a bar is fixed at S and subjected to a vertical force L, and a moment M at the end N as in *Figure* A(ii), bending moments are induced at the sections A and B. In turn they induce tensile/compressive stresses on the outer fibers at A and B. Four strain gages forming a strain measuring bridge fixed at A and at B are sensitive to the moments at A and B respectively. The outputs from the two strain bridges R_1 and R_2 are thus linearly related to F and M and these can be estimated by solving simultaneous linear equations. When an axial force D acts on the balance at N, it causes bending of the parallel elements A_1 and A_2. Strains near the ends of A_1 and A_2 can be sensed using a strain measuring bridge. The output from this bridge, R_3 is directly related to the axial force D.

It will be seen that D has no influence on the moments at A and B, while F and M do not induce bending of $A_1$and $A_{2.}$ The sensitivities of the balance to F, M and D can be adjusted by varying the sections at A and B, and thicknesses of A_1 and A_2. Other dimensions of the bar are determined by stiffness and size constraints of the application.

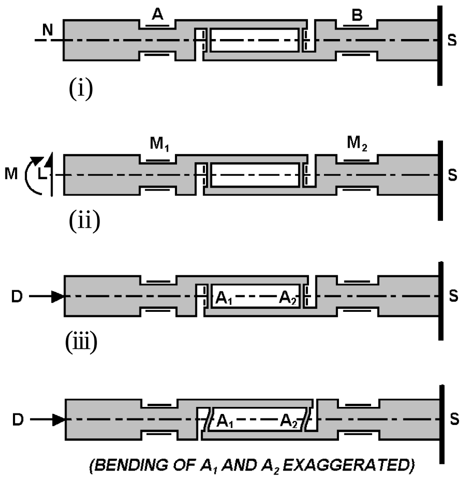


Figure A. Principle of the wind tunnel balance. This shows a balance for measuring three force components – lift, pitching moment and drag. The bending moments at A and B are proportional to a linear combination of lift and pitching moment (L and M). Strain gages at A and B are sensitive to these bending moments. The elements A_1 and A_2 are subjected to bending due to the drag D. The strain gages on A_1 and A_2 are sensitive to this bending. L and M induce little bending of A_1 and A_2 .Thus strain measurements at A, B and A_1/A_2 can be used for calculating L, M and D respectively after appropriate calibration.

Here {R} is the response which is a column matrix of sensitivities to the applied forces {F}, and [C] is a 6 by 6 calibration matrix. Ideally [C] will be a diagonal matrix as the non-diagonal terms represent cross-sensitivities of the measuring elements and are made small by careful design. For use, the relation given by (1) can be inverted to get

$$\{F\} = [U]\{R\} \quad . \qquad (2)$$

Here, [U] is the inverse of [C] and is called the user matrix. During a tunnel test, {R} will be measured and the aerodynamic forces {F} are calculated. These forces/moments which are specified in the balance-axis system can be transformed into any other axis system (for example, the wind-axis system) by using suitable coordinate transformations. These calculated forces can be converted into suitable aerodynamic force/moment coefficients by further calculation.

Often, the simple procedure indicated above is not sufficiently accurate as it does not take into account the elastic deformations of the balance itself. Corrections to the measured incidence and nonlinearity of the balance due to the balance deformation can be considered. But this greatly increases the complexity of force measurements. This complexity is justified when the accuracy requirements are particularly high.

Suggested Reading

[1] Milton Van Dyke, *An Album of Fluid Motion*, The Parabolic Press, Stanford, California, 1982.

[2] Jewel B Barlow, William H Rae and Alan Pope, *Low-Speed Wind Tunnel Testing*, John Wiley and Sons, Inc., New York, 1999.

[3] Gerald Corning, *Supersonic and Subsonic Airplane Design*, Post Box 14, College Park, Maryland, 1953.

Address for Correspondence
S P Govinda Raju
Department of Aerospace Engineering
Indian Institute of Science
Bangalore 560 012, India
Email:spg@aero.iisc.ernet.in