The Principles of hovercraft design

P. FitzPatrick - Hovercraft Club of Great Britain (S.E. Branch)

The simplest form of hovercraft, or more correctly air cushion vehicle (ACV), is the hover-skate. This is a device used in factories for moving heavy loads. It is essentially a disk or rectangle of steel with a side-wall, like a biscuit tin lid. They usually have a rubber seal around the edge to accommodate irregularities in the floor surface.

An air supply hose is connected to the skate. This forces air into the skate at a pressure approximately equal to the mass to be moved. The volume of air supplied must be sufficient to overcome the air lost around the edge of the skate when it is hovering.

E.g. A load of 8000Kg must be moved using 4 skates. Each will need to lift 2000Kg

If each skate measures 1000mm x 1000mm the area of the skate is 1m/sq the air pressure (cushion pressure) required to lift the mass is therefor 2000Kg/m sq (19.6 Kpascals or 2.84 psi)

$$\text{Cushion pressure} = \frac{\text{Total weight of skate and load}}{\text{area of cushion}}$$

Note: in the example above the weight of the skate in comparison with the load is negligible and has been ignored. In hovercraft both craft and payload must be considered.

The edge of the square skate, under which air can escape when the pressure lifts the skate, will be 4x 1000mm (ie 4 mtrs.)

Assuming that the skate is designed to hover just 3mm (hover-gap) off the floor, the total area through which the air will escape (*Ae*) is (4 x 0.003) m sq or 0.012 m sq

To calculate the volume of air passing through the hover-gap we need to consider some basic principles of air movement.

Definition of Pressure

Atmospheric air experiences a pressure from the weight of air above it. At sea level this is 1 Bar or 100,000 Pascals (Pa). Air blown into a child's balloon is described as being "under pressure" and is likely to be only a little above atmospheric pressure – perhaps 105,000 pascals. The term "Pressure" without qualification, describes both the air outside the balloon (Po = 100,000 Pa) and the air inside the balloon (Pa = 105,000 Pa). This form of pressure can be particularised as *absolute pressure.*

Static Pressure Ps $\qquad Ps = Pa - Po$

For the purpose of fan and air movement engineering, static pressure can be considered as the difference between the absolute pressure of the point under consideration and atmospheric pressure. In the case of the balloon the static pressure would be the absolute pressure inside – atmospheric pressure outside or 105,000 – 100,000 = 5000 Pa. Static pressure is positive when above atmospheric pressure and negative when below.

Velocity Pressure Pv $\qquad Pv = \frac{1}{2} \rho v^2$

Where ρ (Rho) = 1.22 the density of air in Kg/m sq at sea level and v = velocity of air in m/sec

When wind exerts a force on an object (e.g. a round chimney) the pressure on the windward side is greater than that on the opposite side. The wind will flow around both sides of the object. At the point where the flows separate, there is a point where the velocity is zero. This is called the stagnation point.

From the velocity pressure formula above it will be seen that if v=0 then Pv = 0

Total Pressure (*Pt*) $Pt = Ps + Pv$

As the wind is flowing through the atmosphere without exerting force on anything the static pressure will be zero. The wind however has velocity and therefor a velocity pressure. When it meets an object as above, at the stagnation point where the velocity pressure falls to zero the static pressure will rise to equal the value of the velocity pressure thereby exerting a force on the object. Velocity pressure is always positive.

These principles are also true for air flowing in a duct. Due to friction the duct offers a resistance to the flow of air and the air exerts a static pressure on the walls of the duct. Because the air is flowing through the duct it also has velocity pressure. In a ducted air system, the fan imparts a total pressure (*Pt*) rise, which is then constant throughout the system. As $Pt = Ps + Pv$ any change in Ps results in an opposite change in Pv When the air leaves the end of the duct it has only velocity pressure which is equal to the total pressure, i.e. the static pressure falls to zero.

Applying this to the original example of the hover skate.

The Cushion pressure (*Pc*) is 19,600 Pascals. This is a static pressure exerted on the floor and walls of the plenum formed under the skate.

So $Ps = 19{,}600$ Pa. hence (Eq A) $Pt1 = 19{,}600 + Pv1$
(where the suffix 1 represents the conditions within the cushion)

When the air leaves the cushion (Eq B) $Pt2 = Ps2 + 19{,}600$
(Where the suffix 2 represents the conditions outside the cushion)

As stated above when the air leaves the system all of the static pressure is converted to velocity pressure
So equation B can be re-written as (Eq C) $Pt2 = 0 + 19600$ Pa and (Tot Press. = Vel Press.)
Equation A can be re-written as (Eq D) $Pt1 = 19600$ Pa $+ 0$ (Tot Press. = Stat Press.)

This ignores any velocity pressure within the plenum, but as this tends to be very low in comparison with the cushion or static pressure, neglecting it makes very little difference to the final calculation.

Knowing that Velocity pressure ($Pv2$) $= \frac{1}{2} \rho V^2$

We can re-write equations B and C to form $19{,}600 = \frac{1}{2} * 1.22 * V^2$

And transpose to arrive at $V = \sqrt{\frac{2*19{,}600}{1.22}}$ = 179.25 mtr/sec

$$Ve = \sqrt{\frac{2Pc}{\rho}}$$

This is the escape velocity (*Ve*) of the air where it escapes through the hover-gap at a given cushion Pressure (*Pc*)

The Volume of air lost (Vol) = Escape Velocity (*Ve*) * Escape Area (*Ae*)

Vol = 179M/sec * $0.012M^2$

= 2.15 M^3sec

So each skate requires 2.15 M^3sec of air at 19,600 Pa

The calculations above are based on ideal airflow. They have been simplified and take no account of turbulent airflow, frictional losses, or variations in air density. The final conclusions will therefor render answers slightly higher than would be expected in real situations.

<u>HOVERCRAFT</u>

The principles above are as true for hovercraft as for the skate. But due to the dynamic nature of a hovercraft more things need to be considered in the design.

As above to calculate the cushion pressure and volume of air required it is necessary to know

1. the craft weight
2. the design payload
3. the length of the contact point of the skirt (perimeter length of cushion footprint)
4. the area of the cushion footprint

Hovercraft are usually powered by propellers or fans. Where independent driven fans are used for lift and thrust, the calculations are simpler because the lift fan can be set to run at a constant speed (and airflow) for given operating conditions. On such a craft some allowance must be made for variations in operating conditions.

As the cushion pressure is selected to offset the total craft weight and thereby provide lift, any change in craft weight or payload, will require a change in cushion pressure. Any change in hover-gap will result in a variation of air volume required to maintain the cushion. In practice this variation occurs with the change in surfaces over which the craft is travelling. As a consequence, it is necessary for the lift fan selected, to supply sufficient pressure and volume in these different conditions. This ability is dependent on the characteristics of the fan selected, and the rotational speed at which it is used.

Where an integrated system is used, having just one driven fan used to supply both lift and thrust, the problem becomes more complex. It is generally required that the thrust is adjustable, usually by throttling the drive engine. This inevitably means that the lift air is throttled at the same time. It therefor becomes necessary to balance the lift system, such that full lift is acquired at less than full revs of the engine. This allows part throttle manoeuvring for turning etc without losing lift and gaining too much drag from the skirt. The inevitable consequence is that at maximum engine speed, more lift air than is actually required is being supplied to the cushion, with an associated waste of power.

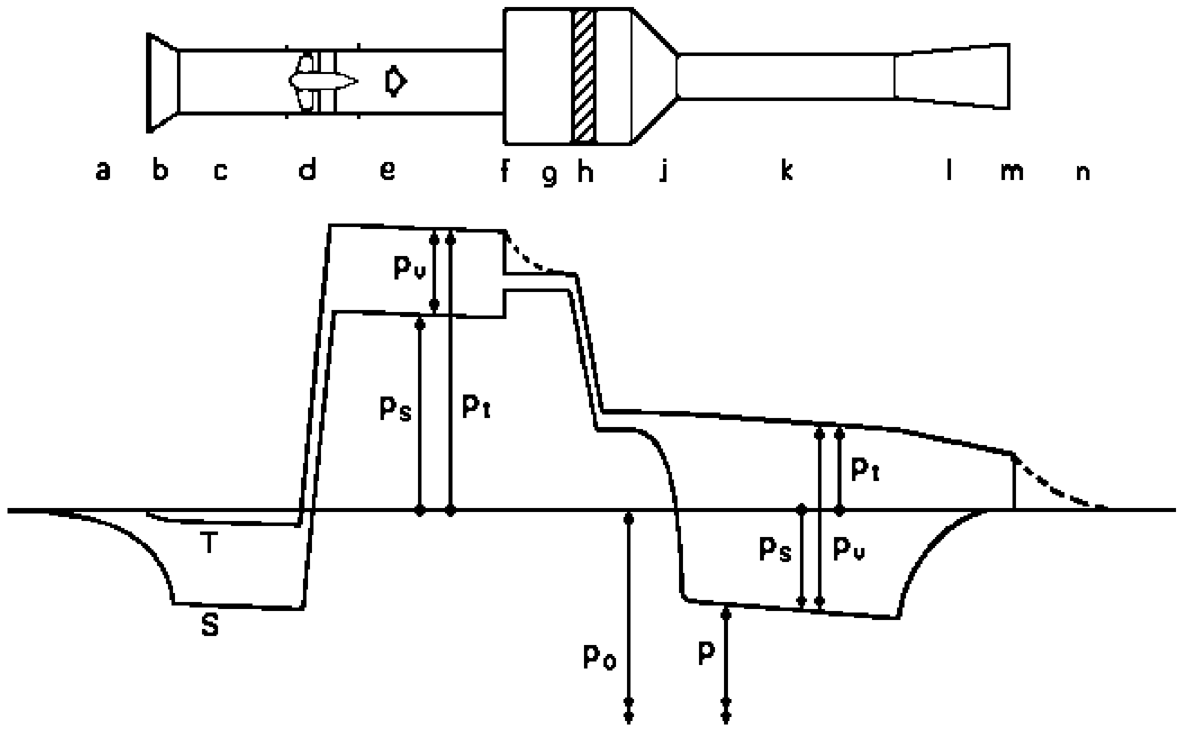
Pressures in a Ducted Fan System

Fig. 1.0 illustrates most of the definitions of pressure, which have just been discussed. The heavy lines S and T follow the changes of static pressure and total pressure respectively from inlet to outlet. *Po* is the atmospheric pressure and *P* the absolute pressure in the duct, both measured from an absolute zero far below the bottom, of the page. The other quantities can be identified by the arrows on the diagram, as:

$$Ps = P - Po$$

$$Pv = \frac{1}{2} \rho V^2$$

$$Pt = Ps + Pv$$



© Woods practical guide to fan engineering

Fig. 1.0

Following the lettered stages through the system with reference to the fig. numbers where numerical data will be found:

a. Air velocity increases from zero in the free atmosphere towards the duct entry. There is no loss, so *Pt* is constant at the free atmosphere zero value. As V increases *Ps* falls with

$\frac{1}{2} \rho V^2$

b. Small drop in *Pt* corresponding to entry loss.

c,e. *Pt* falls gradually at friction gradient.
Pv is constant and *Ps* = *Pt* - *Pv*.

d. *Pt* rises by the fan total pressure. In the diagram *Ps* rises by the same amount, but this is only because inlet and outlet areas are equal in the case illustrated. Note that the change in *Ps* is never equal to the "fan static pressure".

f. When the duct area is suddenly enlarged, *Pt* will fall corresponding to the loss of energy. The nominal fall is sharp, as shown by the full line. The broken line illustrates the lengthways distribution of energy loss, which in fact occurs. *Ps*. will rise sharply, both nominally and actually as measured by the wall pressure. This, "static pressure regain" arises because the whole of the drop in kinetic energy from e to g is not lost.

h. The drop in *Pt* here represents "useful work" that has been done in overcoming the flow resistance of a necessary element in the system-for example a heater battery. *Ps* drops by the same amount because Vg has the same, low, value both approaching and leaving the battery.

j. The air is accelerated with little loss of *Pt* but with a large fall in *Ps*, corresponding to the large rise in *Pv* to $\frac{1}{2} \rho V_k^2$

k. *Pt* and *Ps* fall with pressure gradient corresponding to the velocity in duct k-which is greater than that in duct c.

1. The gradual increase of duct area is accompanied by a moderate energy loss and drop in *Pt* together with a substantial "static pressure regain" in *Ps* associated with the large drop in V. This is an example of a diffuser deliberately inserted to improve the efficiency of the system.

m. At any system outlet to the free atmosphere, the whole of the kinetic energy of the flow will be lost. Thus, in contradistinction to the inlet a, where *Ps* fell and *Pt* remained zero, at an outlet *Pt* will fall from its value just before the outlet to zero while *Ps* will reach zero before discharge at m, and remain zero.

n. The broken line again distinguishes the actual loss of energy along the outlet jet, from the sharp fall in nominal *Pt* at m.

As can be seen from the description above, an ideal duct is one where no energy is lost by the air after it's energy level is raised by the action of the fan, except when the energy is used to do useful work.

This is of course impossible, as losses occur due to friction, change of duct size and shape (bends etc.) For practical purposes, the best design of duct, is one which uses these basic principles to minimise all losses and uses almost all of the energy available from the fan to do the useful work.

This requires that

1. The most suitable sizes of ducts are chosen at the design stage.
2. Changes of shape are kept to a minimum and where necessary are gradual.
3. All bends and other elements are designed to minimise friction, turbulence and changes in static pressure.
4. The total pressure available at each point within the system is utilised by keeping control of the both static and velocity pressures within the design.

<u>Bibliography</u>

Woods Practical Guide to Fan Engineering. BB Daly
Fans. Osbourne. Pergamon Press Oxford
Homebuilt Hovercraft. Flight International Supplement 1964