Mechanical Forces Developed in Pianola Pneumatic Motors

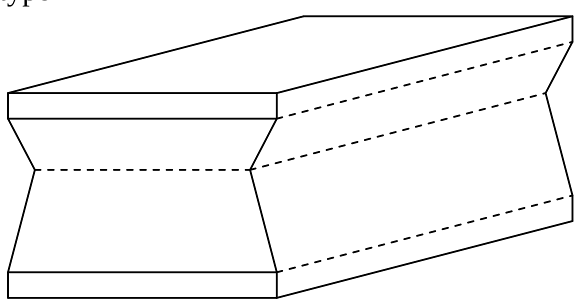
1. Introduction.

The author started work on this paper some 20 years ago. Recent events have stirred the author to complete the work and to publish. MMD archives is a suitable place for publishing. As a related problem, the author worked with an Australian manufacturer of pneumatic cloth to establish a suitable product and manufacturing specification. This work will possibly be reported at a future date.

2. Basic pneumatic motors.

These items consist of (generally) two pieces of timber, joined together with an air-tight flexible cloth. By evacuating air from the inside, the resulting difference in air pressure causes the two pieces of wood to collapse together. The amount of force required to prevent the two pieces of wood closing together depends on the air pressure difference, the area of the wood, the area of the flexible cloth, the type of cloth, and the distance apart of the two pieces of wood.

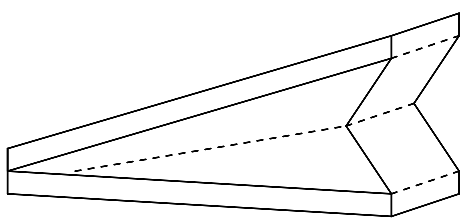
Square type



Motor used in Ampico intensity control.

A second type uses two pieces of wood hinged together. The force developed is subject to the same factors again, but for a given area of wood, the force developed is less.

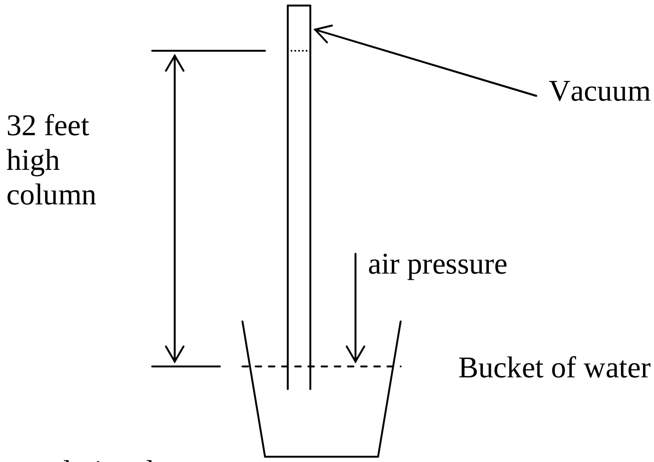
Hinged type



Common air motor type

3. Force development by means of 'Inches of water'.

Low levels of air (and gas) pressure, can be measured in the measurement unit, "inches of water". Normal atmospheric air pressure is about 32 feet of water. That means that the normal pressure of the air will support a column of water 32 feet high.



For a normal pianola,
the height of the column only needs to be 5 **inches** to play softly and up to **40 inches** for a **really** loud ffffff.

Because the air pressures are so low, it is convenient to measure in inches of water. (Normal household gas heaters etc. run on a gas pressure of about 4 to 6 inches of water).

The pressure developed by a column of water can be calculated:

pressure = $\rho \times h$ where ρ, is equal to the density of water and in metric units is 1 gram per cubic cm
h, is the height of the water column in centi-metre

So, for one centimetre height of water, the pressure developed is:

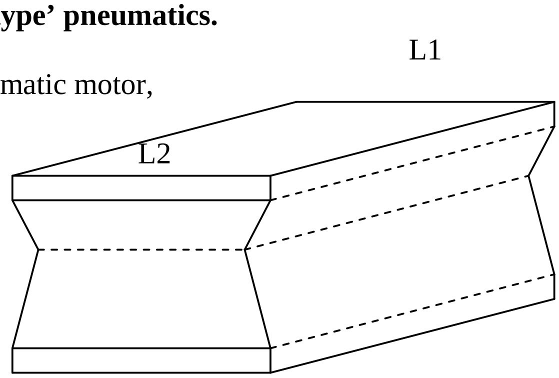
Pressure = 1 (gram/cm3) x 1(cm) = 1 gram per square cm.
This can be converted to pound and inch units by:

Pressure (Lb/in^2) = 2.54 x 2.54 x 2.54 / 453
= 0.0362 Lb per square inch for each inch of water gauge

For example, taking the minimum pressure that a pianola works at (5”), we have,
The minimum pressure is 0.0362 x 5 = 0.181 Lb per square inch (PSI).

4. Force development in ‘Square type’ pneumatics.

Example: Take the Amico intensity pneumatic motor,

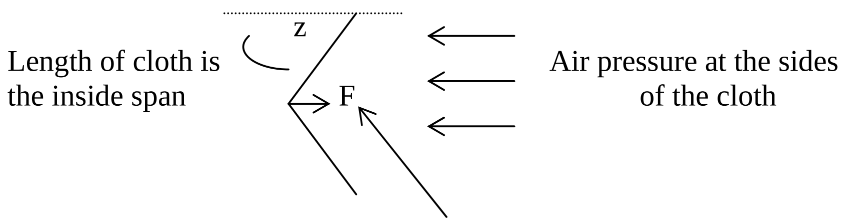


This unit has the dimensions;
Boards: L1=L2 = 1 7/8 “ square
1/8 “ thick
outside span 1 ½ “
inside span 1 ¼”

The force pressing on the top surface is:
P x L1 x L2 =0.181 x 1.875 x 1.875 = 0.636 Lb at 5 “ water gauge (WG).

The force development due to the pneumatic cloth is similar to that developed on the wood. However, this sideways developed force acts to pull the moving board closed through the angle between the cloth and the board. This reduces as the pneumatic closes. When the pneumatic is fully **closed**, the force developed due to the cloth is zero.

Section view of bellows cloth



F is the force needed to resist the air pressure = cloth force:

(In fact, the cloth is curved in the shape of a catenary, but the simplifying assumption is made that the cloth is straight sided with a sharp crease along the centre line)

Cloth force is equal to (L x inside span x vacuum pressure). This force acts on the wood through the angle 'z'. WE can express the angle z as a function of the fraction of the full ***internal*** span that the pneumatic is open. When fully open, the angle z is zero(0). When 90% open, the angle is arcos 0.9 = 25.84 degree and tan 25.84 = 0.484 . (Actually we use half the span and then there are 2 halves along the crease line)
So the force developed by the **cloth** on the moving board at 5" WG is:

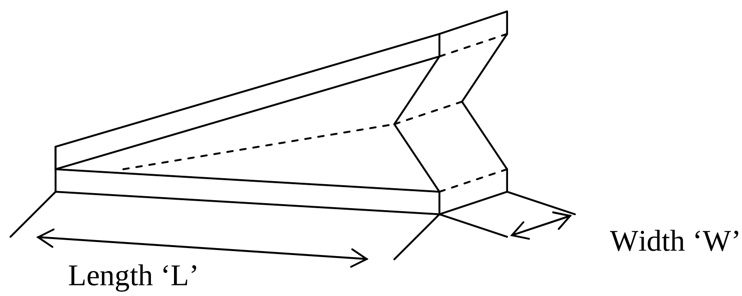
F = 2 x (P x L x (inside span)/2)/(tan z) = (0.181 x 1.875 x 1.25)/(tan z)=0.212/tan z for one of the 4 sides of the pneumatic. Since there are 4 sides, the total force due to the cloth is; = 1.70 / tan z Lb. at 5"wg
The force developed by the wood top is P x L x L = 0.636 Lb
We can list the forces in a table of values for the intensity pneumatic at a pressure of 5 inches WG.

Force due to the wood Lb	Degree of opening %	tan z	Force due to the cloth Lb	Total force developed Lb
0.64	100(full open)	0.0	∞	∞ **
0.64	90	0.48	3.54	4.18
0.64	80	0.75	2.27	2.91
0.64	70	1.02	1.67	2.31
0.64	60	1.33	1.28	1.92
0.64	50	1.73	0.98	1.62
0.64	40	2.29	0.74	1.38
0.64	30	3.18	0.53	1.17
0.64	20	4.9	0.35	0.99
0.64	10	9.95	0.17	0.81
0.64	0	∞	0.00	0.64

** The value of 'infinity' is by calculation. However it does show that a very high force can be developed when the pneumatic is ***fully*** open.

At the 40 % opening, the force is about half due to the wood, and half due to the cloth. The force is considered to be developed at the geometric centre of the top board. These data are for an unhinged pneumatic, like the intensity pneumatics of the Ampico ‘A’ intensity controller. The tabulation of tan z versus percentage of opening is practically valid for ANY pneumatic

5. Force development in hinged pneumatics. (Two deck pneumatic)
The calculation is complicated by the taper arrangement of the boards and the side cloth. Simplifying assumptions are made as for the square pneumatic.



Force due to the wood, calculated at the moving end is:

$$F_{wood} = (P \times W \times L) / 2$$

P is the pressure as before, and at 5” water gauge

$$F_{wood} = (0.181 \times W \times L)/2 \quad \text{Lb force}$$

The force due to the cloth at the moving end is, as before,

$F_{endcloth}$ = 2 x (P x L x (inside span)/2) / (tan z)
= 0.181 x W x inside span) / tan z

The force due to the cloth at the sides is (both sides):

$F_{sidecloth}$ = (1/3) x (P x L x inside span) / tan z

(The factor 1/3 , is derived from an element of force using a double integral, integrated over the length L, and from the centre line to the wood.)
Not all the cloth material is effective. The end cloth effectiveness is reduced by the cloth folds at the end. The folds along the sides tend to prevent the end cloth collapsing along its centre line. The effective width of the end cloth is reduced by the span. We can take the effective end width of the cloth to be equal to the width minus the inside span. This is a "fiddle factor" and is an assumption. This number, however, cannot be negative.

Taking the note playing pneumatic for an Aeolian player, we have;

L = 4 1/2 inch	W = 29/32 (0.905”) inch
Outside span = 1 1/8 inch	inside span = 0.71 inch

Force due to the wood (at 5” WG): = 0.181 x 0.905 x 4 ½ / 2 = 0.37 Lb.
Force due to the end cloth (at 5” WG) = (0.181 x (0.905-0.71) x 0.71) / (tan z)
= 0.03 / tan z
Force due to both side cloths (at 5” WG) = 0.333 x 0.181 x 4 ½ x 0.71 / tan z
= 0.19 / tan z

These calculations give the theoretical forces developed. The force development can be considered to be concentrated at the end edge of the moving board.
In practice, there will be other 'closing' forces which will operate to ***oppose*** the closing of the pneumatic.
These include:

- The mass of the wood as well as the fabric connected to the moving board; the mass of the moving board and cloth has to be supported.
  In practice this is a minor effect
- The stiffness of the fabric. At the moving end of the pneumatic as it closes, there are SIX layers of cloth. As the moving board closes, these fabric layers become harder to compress. In the column, 'closing force', the test data shows that the cloth material develops significant resistance to closing when the pneumatic is nearly closed. If a bumper is used inside the pneumatic to prevent the moving board crushing the cloth, it should not interfere with the folds of the cloth at the moving end and its size and position needs to be considered accordingly. The bumper prevents full closure of the moving board and consequent crushing of the cloth folds. Typically, the minimum % opening cannot fall to less than 10%. The maximum span of the moving board is typically not more than 90% of the maximum inside span.

In another paper (yet to be published), we give the criteria for the design of the rubber covered pneumatic cloth. Not-withstanding the characteristics of this material, at low vacuum levels, the 'closing' forces of the pneumatic motor have a great influence on the calculated performance. Practical assessment shows the pneumatic is seldom open to more than 90% of the assembled span. Further, experience shows the minimum closure is around 2 to 3 mm (3/32 to 1/8 "). For the Aeolian pneumatic this amounts to a minimum closure of 10 %. The table of forces in the table below is given between 10% and 90% of the maximum span.

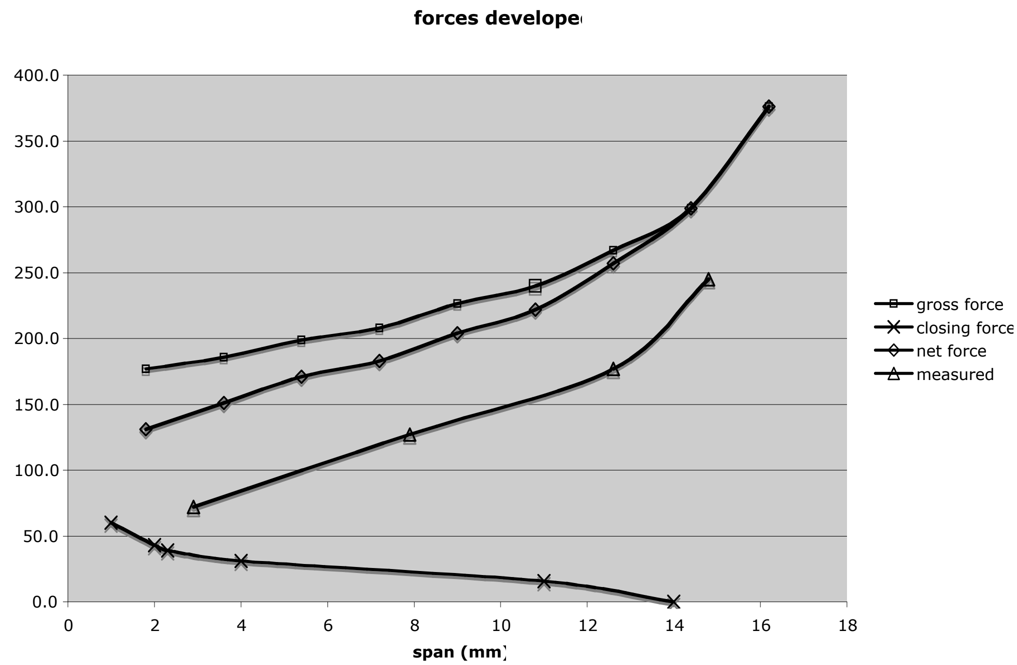
The table gives the values.

Force due to wood Lb	Percent opening %	tan z	Force due to end cloth Lb	Force due to side cloth Lb	Total force developed Lb	Closing force (cloth effect) span %	Closing force (cloth effect) force(g)
0.37	90	0.48	0.06	0.40	0.83	78	0.0
0.37	80	0.75	0.04	0.25	0.66	62	15.6
0.37	70	1.02	0.03	0.19	0.59	25	31
0.37	60	1.33	0.02	0.14	0.53	14	39
0.37	50	1.73	0.02	0.11	0.50	12	43
0.37	40	2.29	0.01	0.08	0.46	6	59
0.37	30	3.18	0.01	0.06	0.44		
0.37	20	4.9	0.00	0.04	0.41		
0.37	10	10	0.00	0.02	0.39		

The closing force was measured on a test sample pneumatic of no particular virtue. Note that the 'force' data is in gram. The data was plotted, smoothed and interpolated to give a value applicable at the 'percent opening' data points. The practical

measurement set-up is best described as 'agricultural'. The place of measurement of the closing force is at the end edge of the moving board.
The data smoothing combined with the measurement units used, may give some confusion and for this the author apologises.

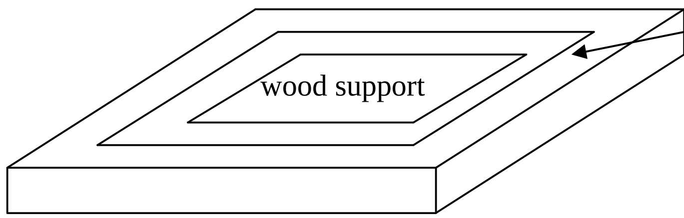
The attached graph plots
- total force calculated
- closing resistance force measured
- net force calculated (1 – 2)
- measured force on actual pneumatic



The measured force shows some discrepancy with the calculated value. What is confirmed is the higher developed force when the pneumatic is open compared to that when closed. These data are taken at a vacuum level of 5 inches. The data also shows the increasing closing resistance force as the pneumatic closes. The closing resistance force is a significant proportion of the total developed force measured at a percent opening of 10%. (around two to three mm)
For a manufacturer of pneumatic cloth, the closing resistance force is an interesting concept but unsuitable for product assessment at the time of manufacture, whereas closing force is a critical factor in assuring a reliable playing performance at low vacuum levels. Work done by the author suggests that closing force for cloth materials is typically 50 to 60 gram but poor materials can show values of 80 to 90 gram whereas materials designed for low closing force show values in the 20 to 30 gram range. At 5 inches of vacuum, the gain in force between 'good' and 'poor' materials is equivalent to additional vacuum levels of around 1 to 1.5 inches. These benefits are worthwhile for those attempting to achieve top performance at low vacuum levels.

6. Force development in three deck pneumatics.
Three deck pneumatic boards use wide motors which are generally shorter than those of 2 deck designs. The theory is as above. While the author has both types of design, not much work has been done to relate actual test results with the design theory. The Simplex unit type is a three deck design.

7. Force development in Angelus type pneumatics.
This design of pneumatic motor is different to other types in that the developed force is entirely due to the surface area of the wood only. There is no folding of the cloth and the direction of force on the cloth is parallel to the direction of force on the wood.



Given a size of the outline edge of the cloth of 2 7/8 " x 2 ½ " gives a force, at 5" vacuum of; 0.181 x 2.875 x 2.5 = 1.3 Lb. (590 gram). Because the developed force is ALWAYS perpendicular to the direction of the motion, the force is constant with respect to the displacement. If this characteristic were to be drawn on the graph above, the line would be parallel to the base line at 590 gram. According to the information in Durrel Armstrong's catalog, the likely range of movement is only say 10mm. It is likely that the wire coupling piece gives some multiplication of the movement (and the developed force) of the pouch board to the finger.

8. Discussion.

This analysis was started in about 1990. The author had reconditioned a Simplex unit pneumatic player with a cloth made by Archer in Massachusetts. This was the authors first rebuild. Next, a H.C. Bay action was reconditioned, this time using an Australian made cloth. Unaware of the requirements of light-weight pneumatic cloth, the reconditioned machine was almost impossible to play because the pneumatic cloth was more like hessian sack cloth. It was this experience which lead to the mathematical analysis, and further, to work with a local cloth manufacturer, to establish a performance and a manufacturing specification. The work largely went astray, because several of the purchasers of the cloth had different interpretations of what they wanted in a cloth. Only recently, the author has looked at the MMD archives to find that indeed, many people have different perceptions of what is required of a pneumatic cloth suitable for recovering note playing pneumatics. Without being too dogmatic, it is certain that complaints about pneumatic cloth revolve around the issues of longevity and ability to play the pianola at low playing levels and to achieve an evenness of playing notes at low vacuum. What can be said is that no contributor has been able to provide a manufacturing and material specification.
This author considers that a pianola should be able to play evenly at a minimum vacuum level of half, to one, inch of vacuum, lower than the desired minimum vacuum

level. To achieve this performance requires firstly, a VERY lightweight cloth, and secondly, a lot of careful adjustment effort. The lower is the closing force due to the cloth, then the less variation in playing loudness at minimum vacuum level due to the pneumatic and its adjustment.

There is a discrepancy between the theoretical and the measured value of the developed force for the Aeolian pneumatic. To properly make this test, an accurate jig must be built to allow force, span, and vacuum to be measured. The vacuum system must be leak free or else pressure (vacuum) loss will affect the measured result. The value of the work was not to prove to an uncertainty of +/- 2%, but rather to confirm the magnitude of the effects.

This has been well enough achieved, and in particular, the increasing influence of closing force as the pneumatic collapses has been confirmed. Having arrived at a value for closing force, the next step was to determine how to manufacture a cloth to achieve the required maximum permissible closing force.

In essence, the cloth weave determines the quantity of rubber to be used to achieve a satisfactory pinhole level. Having determined this, the material is assessed for closing force against rubber thickness. If the force is too high (say > 70g) then the cloth weave is too coarse, and a higher thread count of finer thread (more expensive) is required.

Using finely woven cloth, (>100 threads per inch IN BOTH DIRECTIONS), with a rubber thickness measured in gram per square metre), a cloth with closing forces in the 25 to 45 gram can be produced at will.

Paul Rumpf.
Melbourne , Australia,
November 2008.

cos x	x	tan x
1.00	0.00	0.00
0.90	0.45	0.48
0.80	0.64	0.75
0.70	0.80	1.02
0.60	0.93	1.33
0.50	1.05	1.73
0.40	1.16	2.29
0.30	1.27	3.18
0.20	1.37	4.90
0.10	1.47	9.95
0.00	1.57	16331239353195400.00