Thrust measuring test bench (bollard pull)

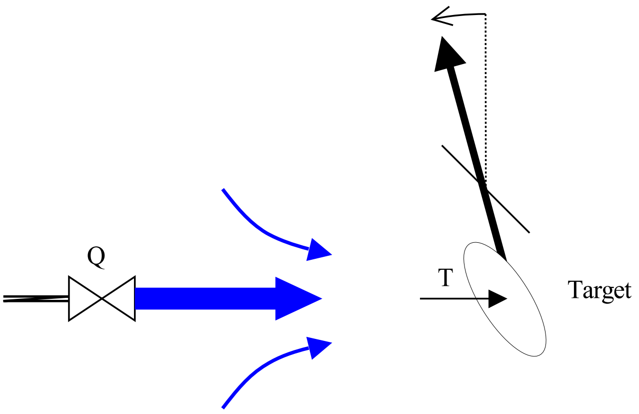
By Jean-Yves

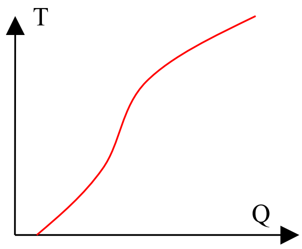
Ultimate goal: to be able to measure and optimize the hydraulic pop-pop engine performances.

To do that, a thrust measuring test bench has been built in the spirit of the "effective flow" measuring one. See document "Hydraulic test bench". This study being a complement of the previous one, to calibrate this bench with permanent flow we reused the water tower. And to calibrate it in alternative flow we reused the pump designed for the previous bench. And in order to be as exhaustive as possible in the analysis of the data, we reused the previous 11 nozzles.

Previously, several thrust measuring devices had given us insufficiently reliable results with pop-pop engines (see annex 1). Moreover, to measure the thrust of a pop-pop engine, it was necessary to fit it on a floating hull. This, added to the drawbacks described in annex 1, made it was difficult to adjust an engine. That is why another way has been explored. By analogy with what was done for the flow, we have done measurements with direct flow Qd to determine the thrust Td, and other measurements with alternative flow Qa to determine the thrust Ta. Then, for every nozzle we have compared the flows Qd and Qa giving Td = Ta.

1°) Measuring principle.





The thrust is not measured directly. In fact it is the deviation of the needle which is measured, but the torque needed to cause this deviation is known. See annex 2.

2°) Thrust measuring tool.

Target rotating around a horizontal axis, weighed, and located in front of the nozzle at a known distance below the axis. See annex 2. Every constitutive part has been weighed with accuracy and measured in order to determine the total mass of the assembly and the position of its centre of gravity. The movements have been limited to small angles, and Archimedes' buoyancy has been taken into account for the immerse portion of the measuring instrument.

3°) Field where the measures are valid.

3.1. Selection of the target shape.

In order to make it receives correctly the water flow, and as little as possible other flows in the tank, a circular target has been chosen. Neither very little, nor very large. After some tests, -and depending on the availability of parts- a semi-spherical target of diameter 34.5mm has been selected. The hollow side has been oriented towards the nozzle for two reasons:

- Better sensitivity (multiplied by 2.5 to 3)
- Better immunity to a possible misalignment regarding the flow.

3.2. Immersion depth of the nozzle.

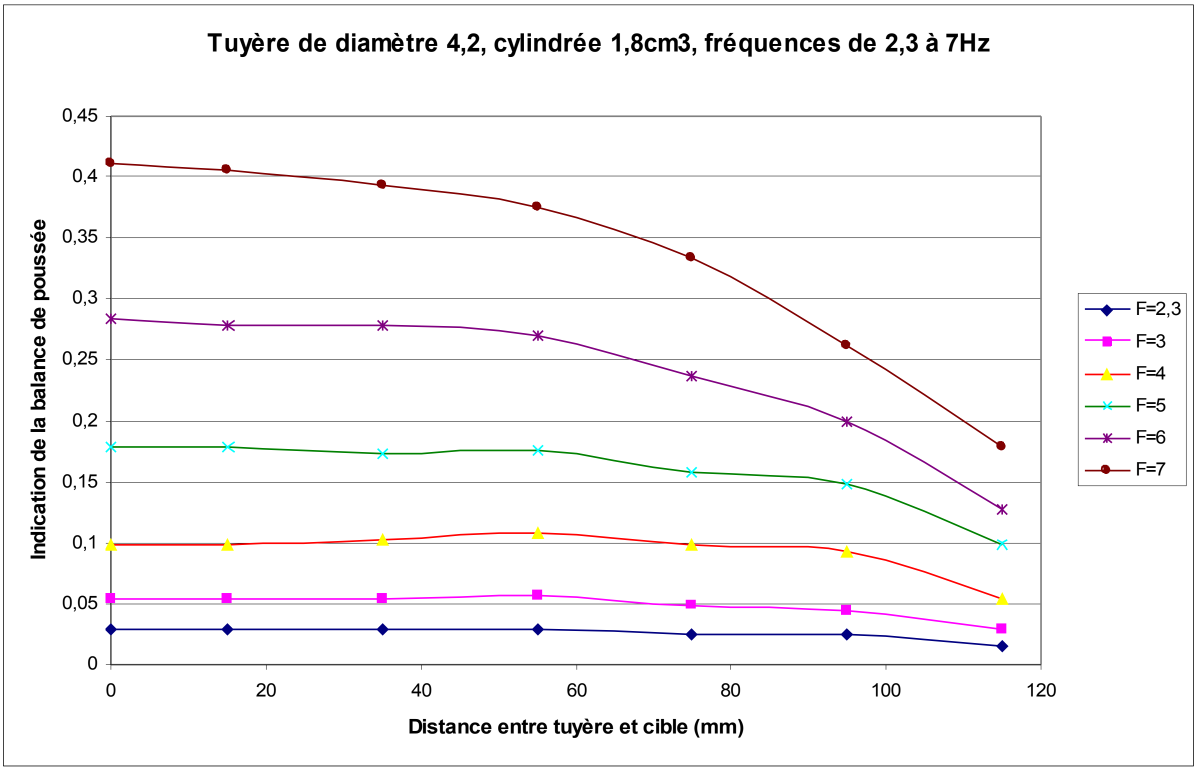
Tests were done with 3 different immersion depths (22.5mm, 42.5mm and 62.5mm). No influence on the measure has been noticed. Then, all the measurements were done with an immersion depth of approximately 25mm.

3.3. Orientation of the target.

It has been checked that up to an angle of 10° the measure was not visibly altered.

3.4. Distance between target and nozzle.

For any of the 11 nozzles some tests were done at 7 different distances, and with flows varying in a ratio of approximately 1 to 10 with direct flows, and 1 to 3 with alternative flows. In this latter case (the worse one) it was visible that below 50mm the measure was practically not influenced by the distance. Example:



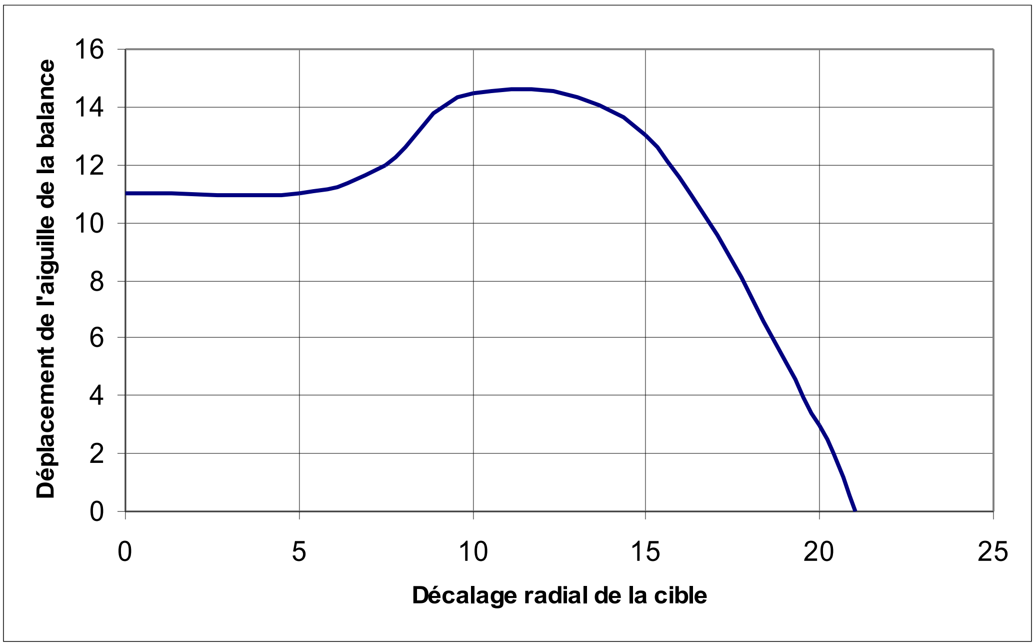
This graph shows the needle deviation versus distance for frequencies 2.3 to 7Hz. Stroke volume: 1.8 cm3. Nozzle diameter: 4.2 mm.

These curves confirm the one published by Professor Le Bot in a French document entitled "Etalonnages de la balance de poussée".

For the following tests, the target was located at approximately 20mm from the nozzle.

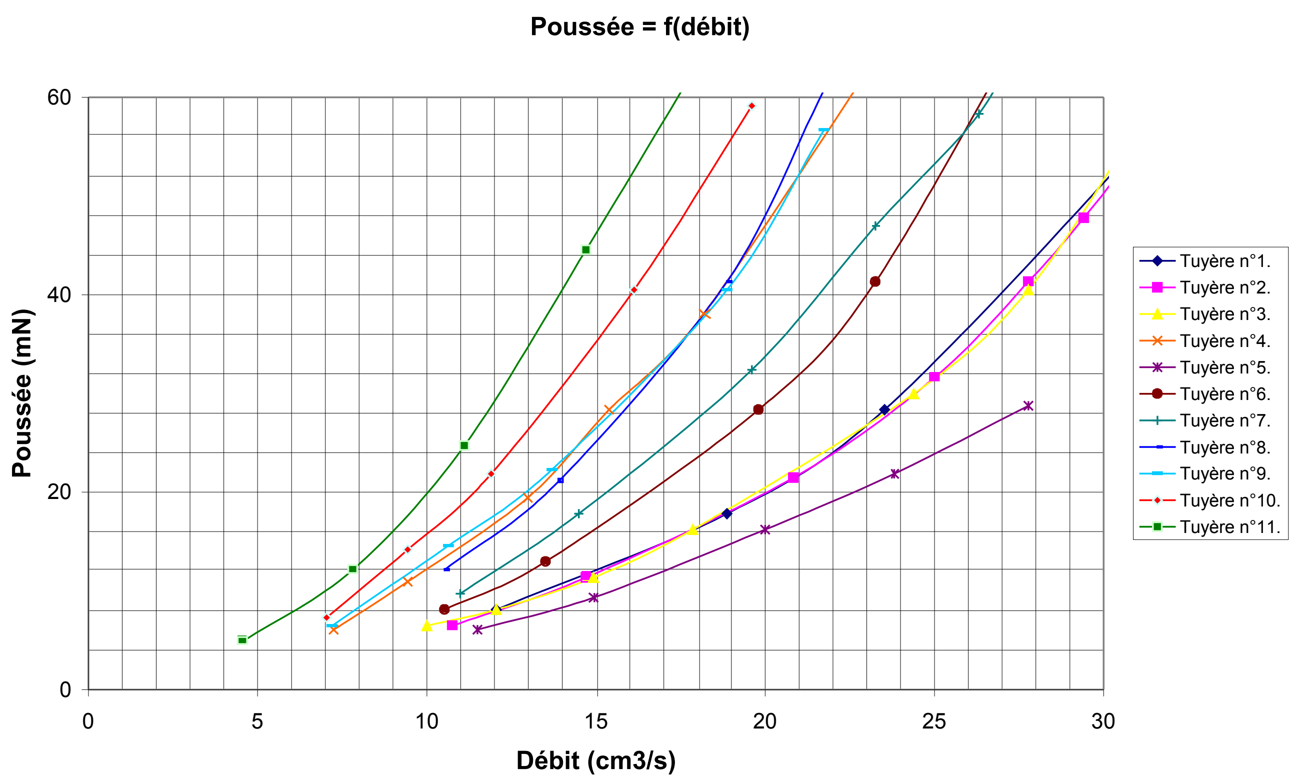
3.5. Misalignment of the target

Due to the shape of the target, a slight radial misalignment (up to 6mm) has no influence. Above 6mm, the measured thrust increases (turbine bucket effect), reaches a maximum of about 130%, and then decreases quickly…the flow going out of the target.



Similar curves were recorded at several distances between nozzle and target. This one was recorded with a 20mm distance.
For the following tests, the target was centered at +/- 2mm.

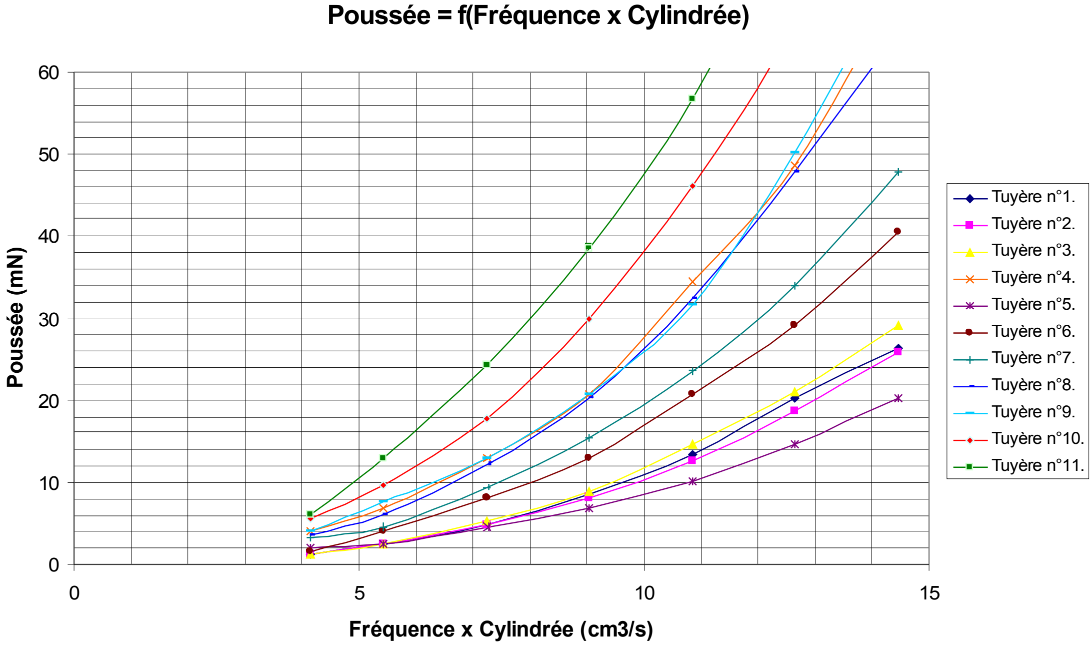
4°) Measurements with continuous flows.



This graph shows thrust versus flow for the 11 nozzles.

The study of every curve allowed us to check that the thrust was evolving as the square of the flow (taking into account the uncertainty of the measurements).

5°) Measurements with alternative flows.

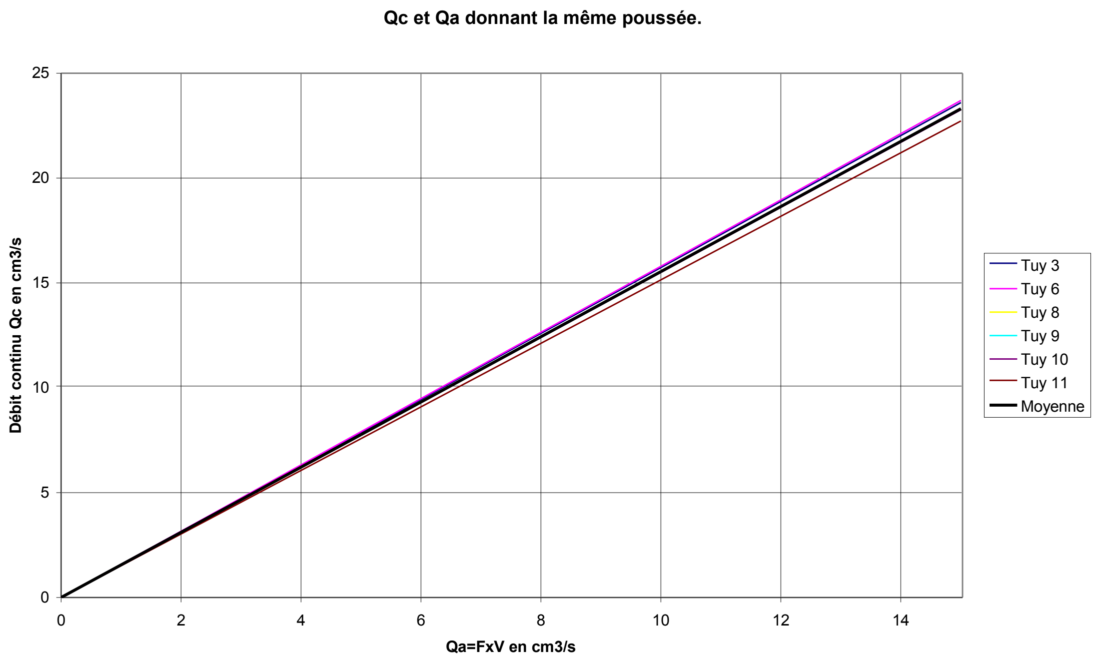


This graph shows thrust versus "frequency x stroke volume" for the 11 nozzles

6°) Comparisons.

By analogy with what was made for the flows (see "Hydraulic test bench") we have compared the continuous flow and the alternative flow that would induce (one or the other one) the same thrust T.

For the 6 most representative nozzles (#3, 6, 8, 9, 10 and 11) that could be the ones of pop-pop engines, the continuous flow average was 1.55 time bigger than the product F x V. And the worse discrepancy was only 2.5%. But the measurement uncertainty is to be added.



7°) Conclusions :

1°) 1°) If we define the flow of a pulsed waterjet by the product *Stroke volume x Frequency*, its effectiveness is higher than the one of a permanent waterjet. The ratio between them is approximately 1.5, whatever the nozzle diameter.

Measurements and calculations were performed with several significant digits. Nevertheless, in spite of carefulness, the measurements allowing to reach this conclusion are not laboratory ones. At this stage, we can compare the global result of the hydraulic test bench (gain 1.48) and the one of the thrust measuring bench (1.55). The truth could be the same in both cases.

2°) It was not the purpose of the tests, but we got confirmation of what we noticed with the hydraulic test bench. For a given flow, the efficiency of a continuous waterjet depends only on the internal diameter of the nozzle. However, an alternative waterjet is more powerful when the nozzle wall is thin and free (in order to ease relaxation and carrying adjacent water).

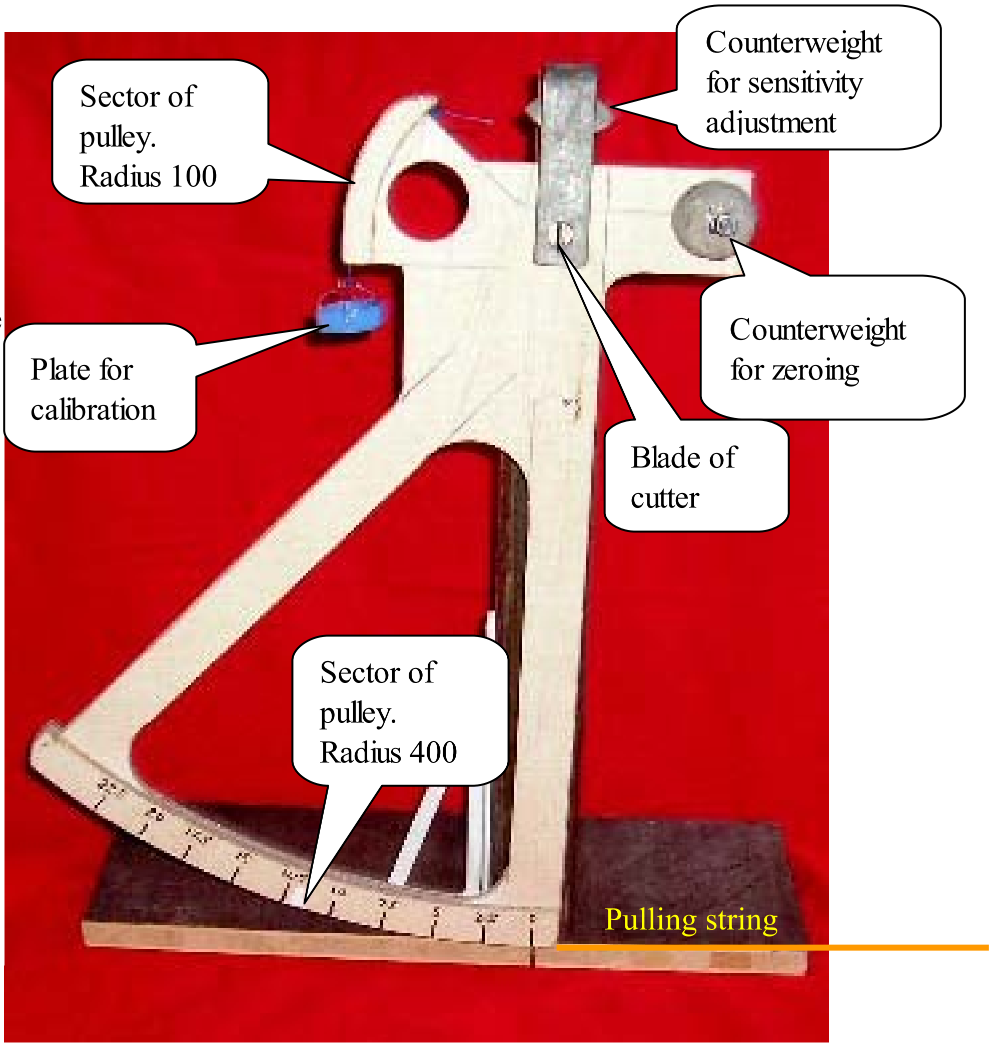
3°) Now we have a tool to test pop-pop engines. First, the test will be the thrust measurement. In addition, the indication will allow us to know the product “Stroke volume x Frequency”. Then, for diaphragm engines it will be easy to know the frequency and hence to deduce the stroke volume. For coil or spiral engines, or for drum ones without diaphragm, a (easy) way to measure the frequency remains to be found to do the same. Thanks in advance for your suggestions.

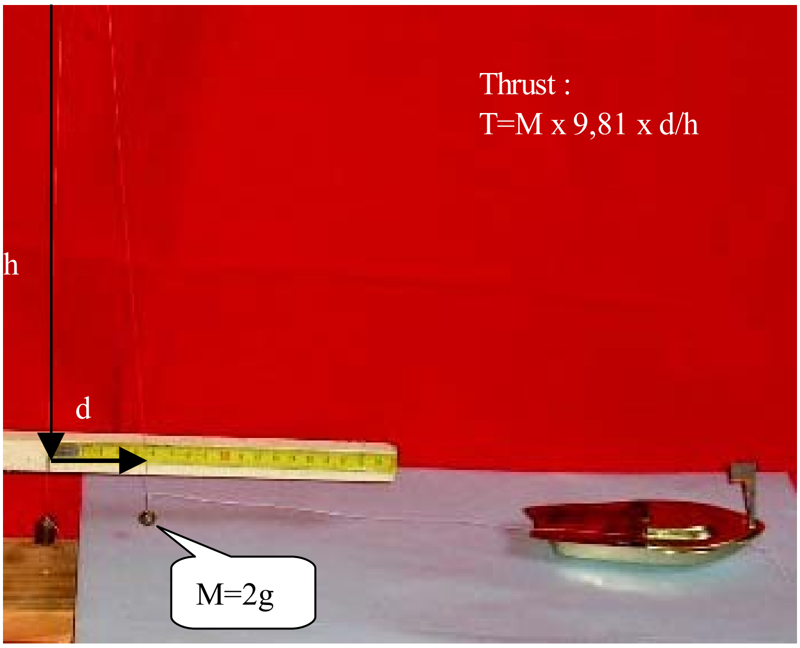
Annex 1.

The thrust measuring device here on the right had many qualities:
Accuracy, fidelity, sensitivity, graduations in mN, pulling direction perfectly horizontal…, but the inertia was too big to use it with pop-pop boats because the thrust fluctuates too much.

Just for information, to give an idea of the inertia and good bearings. After a move of 25° from the rest position, the mobile part oscillated for approx one hour.

For those who would like to join this adventure, we have added some notes on the picture.

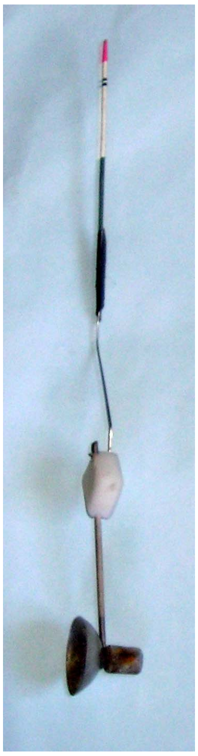




Next, we came back to a classic force equilibrium followed by a simple calculation.
Two pieces of sewing thread, two masses, one of them well known, (the other one being only used for the reference plumb line) and a graduated ruler suffice.
However, the forces exerted by a pop-pop engine are so weak that though a minute mass is used, the string must be long and the problems of instability exist.

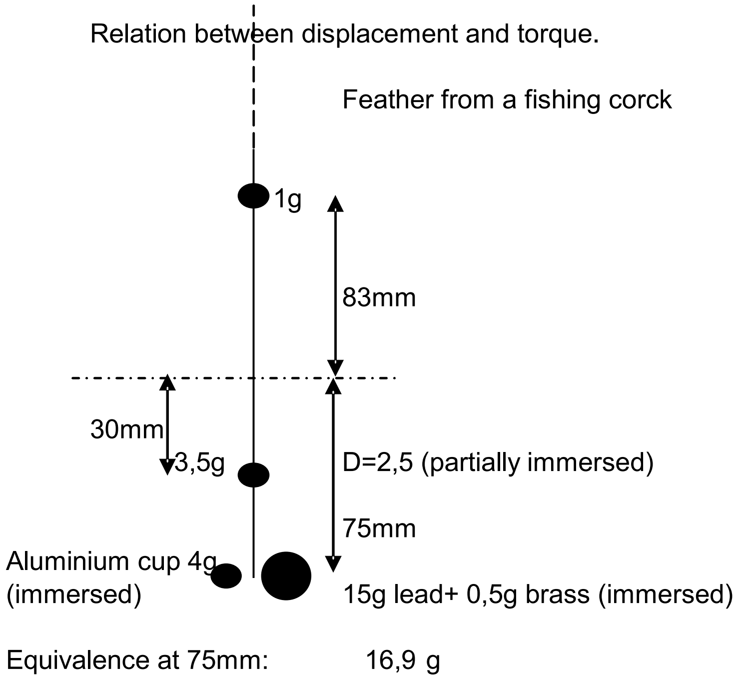
Annex 2.

Thrust measuring device.



The mobile assembly visible on the picture on the left is made of (starting from the top):
A light feather from a fishing cork
A piano string in stainless steel of diameter 10/10
A lozenge in Teflon used as assembling and bearing part.
A stainless steel stem (diam 2.5) flattened and drilled at the lower end.
An aluminium cup to receive the water flow from the nozzle
A 15 g mass made of lead.
A M2 bolt made of brass.

At rest (without thrust) the cup is oriented up by approx 10 degrees. This slight incline has no consequence on the reading and allows using the system on a wider (linear) range.



The mobile part acts as a pendulum of length 75mm and mass 16.9g.
Torque = T x 75
The extremity of the needle moves horizontally of a length `l`. The counter-torque is
Torque = 16.9 x 9.81 x `l` x 75/205
Therefore, the relation between displacement and thrust is T=0.81 x `l` in mN

A confirmation (+/-5%) was got by the use of letter scales. The middle of the cup was on the scales, the axis being horizontal and at the same level as the scales plate.