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A High Precision Double Tubed Hydrostatic Leveling System for Accelerator Alignment Applications

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Since 1998 several hydrostatic leveling systems (HLS) have been installed in different locations at Fermilab. This work was in collaboration with Budker Institute and SLAC. All systems were either half-filled pipe (HF) or full-filled pipe (FF). Issues assembling HLS are covered in this article. An improved and cost-effective water system with temperature stabilized of water media is presented. This proposal is a double-tube full-filled DT-FF system. Examples of hardware configurations are included for systems located at Fermilab.

1. Double-Tube Full-Filled (DT-FF) HLS

Future accelerators will have more stringent alignment requirements. The use of hydrostatic water level systems will be necessary to meet these goals [1]. Many systems are based on pipes half filled with water [2]. The half filled pipe system is rarely used now due to measurement uncertainties caused by thermal gradients along the circuit. Since the specific mass of water changes with temperature (except for water close to 4 ^{0}C) and the temperature is not measured everywhere along the water circuit, the measurement uncertainty Δz is caused by expansion in the vertical parts of the water tubing. The following picture shows variation of water density relatively to density on 4 ^{0}C.

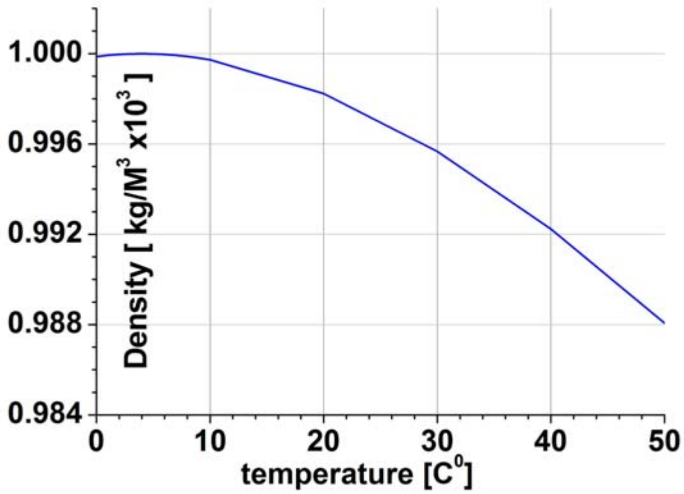


Figure 1 Water density.

For example at 20 ^{0}C a temperature gradient of 1 ^{0}C will cause a difference of 2 micrometers in the surface level of adjacent vessels. Experience at Fermilab with both full-filled and half-filled systems has allowed us to fill in the following table;

Table 1

Properties	**Full Filled**	**Half Filled**	**Double Tubed Full Filled(suggested)**
Temperature stability	Temperature dependent	Excellent	Excellent
Material of tube	Lower cost, transparent Plastic	High cost Stainless tubes	Lower cost, transparent Plastic Common shield for water tubes
Length	length 2xL	Length L	3xL
Supports	No	Strong support	No
Tube Mounting	Simple	In some location – It is impossible! Labor-consuming, Supports Realignment	Simple
Additions	Nothing	Cleaning of tubes, Alignment tools	Need water recirculation system in one of tubes
Total:	Good accuracy Low Cost	Excellent accuracy High cost	Excellent accuracy Acceptable in cost

A double tube system uses three tubes, one for air, one for water that connects all the pools, and a second tube with circulating water to maintain a constant temperature in the other water tube thus eliminating temperature gradients that could affect the water level in all of the pools. Furthermore if the water circulated around the body of the pools the temperature of the sensors and pools would be equalized further stabilizing the system. As a consequence it would be possible to obtain a higher level of precision in level measurements.

2.MI8 HLS – half-filled system

In 2001 a half filled system was installed at Fermilab in the MI8 tunnel [3] consisting of 20 sensors, covering 300 meters [4]. The system used a 25.4 mm diameter polyethylene pipe that was half filled with water. There was also a test device to allow add or remove water.

The test device allowed changing the water level remotely by using RS485 serial card from a PC running a programmed algorithm. This allows for effective testing of dynamic behavior of the system. Mechanics of test device are shown in Figure 2. The submersible Cylinder (7) is mounted on a rod (6) and placed in the tank (9) filled with water. The vertical position of the Cylinder is defined by rod (5). The rod is moved by micrometer (4), which shifts 1 mm per every turn of the motor (1). Connection between the rotor and micrometer is made through coupling (3). All above-mentioned parts are fixed on platform (2). Vertical position of mechanism is established with the three adjustment screws (8). All parts inside water tank are made from stainless steel. The water tank has additional hole on top for balancing air pressure inside and outside of the tank.

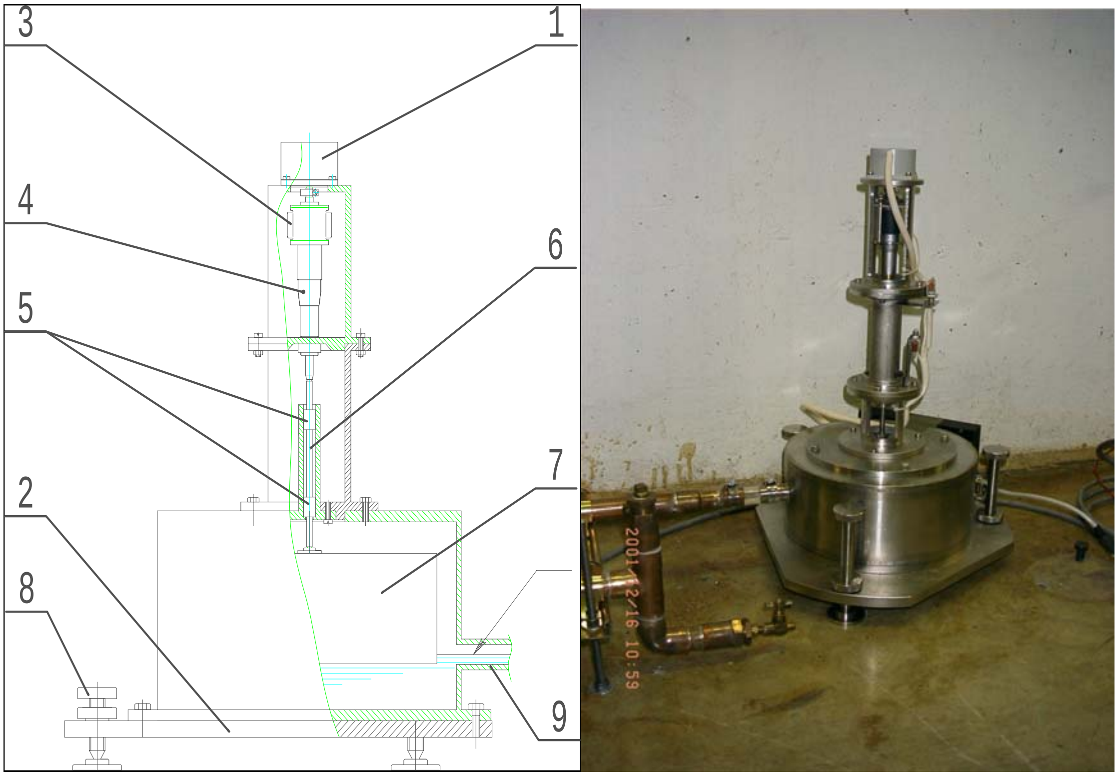


Figure 2 Test Devices at SLAC

Figure 3 shows the dynamic reaction of levels by changing the amount of water at sensor L0. The HLS system took 15 hours to stabilize to +/- 10 micro meters when the mean level was shifted by 100 micrometers.

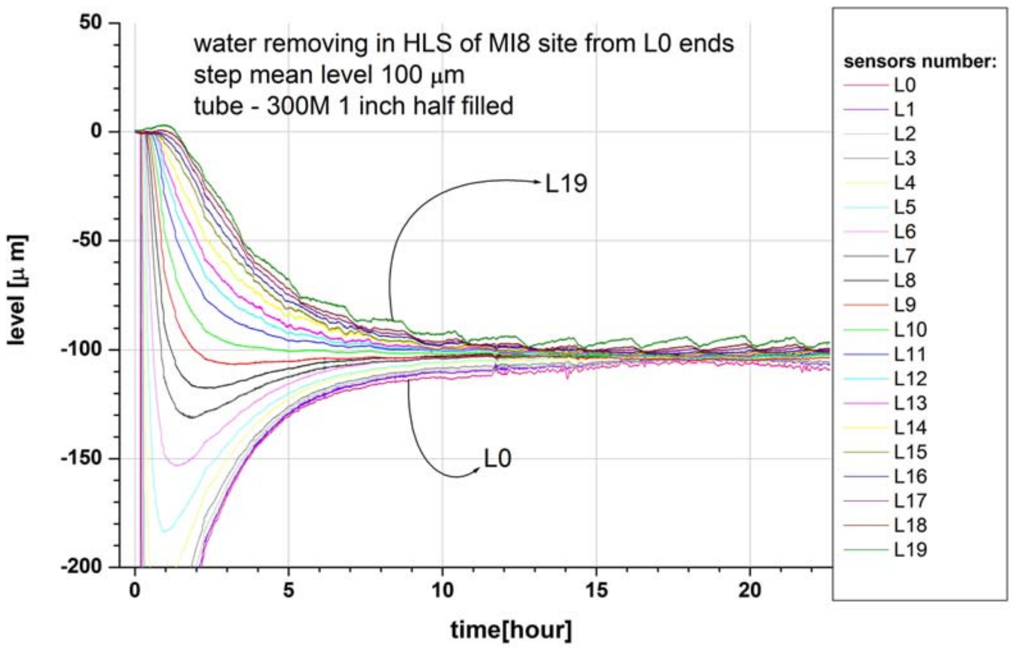


Figure 3 Step reaction HLS in MI8

3. Modelling of HLS

Many accelerator systems need to be stabilized in real time and have component positions adjusted by movers. A vertical motion control system very often uses HLS system in a feedback mode. It is possible to simulate a HLS system to determine the frequency response. Modeling can also be used to predict the behavior of a system before realization to exclude unforeseen circumstances and to avoid significant changes and costs. Modeling also helps to understand the processes occurring in existing systems.

Consider laminar flow of a Newtonian incompressible viscous liquid (water) in a pipe length ℓ and diameter $D_p < \ell$ (model of a simple level gauge). The forces present are:

Inertia: $\frac{\pi D_p^2}{4} \cdot \ell \cdot \rho \dot{V}$;

Shear: $\pi D_p \cdot \ell \cdot \eta \frac{d}{dr} V$;

Gravity: $\rho g y \frac{\pi D_p^{\,2}}{4}$;

Where **ρ**– water density, **η** – absolute coefficient viscosity, **V** – mean velocity, **y** – mean level difference.

The momentum balance is:

$$\frac{d^2y}{dt^2} + 4 \cdot \frac{\nu}{D} \cdot \frac{d}{dr}\frac{dy}{dt} + \frac{g}{L} y = 0 \qquad (1),$$

where $\nu = \eta / \rho$ - cinematic viscosity.

Since **y** is the mean average in cross section, make substituting:

$$\frac{d}{dr}\frac{dy}{dt} = \frac{d}{dr}\frac{d}{dt}\frac{1}{R}\int_0^R y dr = \frac{d}{dt} \cdot \frac{y}{R} = \frac{2}{D_p}\frac{dy}{dt}$$

(2), where R=$\frac{D_p}{2}$ – is pipe radius.

Using (2) give us equation:

$$\frac{d^2y}{dt^2} + 8 \cdot \frac{\nu}{D_p^{\ 2}} \cdot \frac{dy}{dt} + \frac{g}{L} y = 0 .$$

In other form:

$$\frac{d^2}{dt^2} y + 2\omega \frac{dy}{dt} + \omega_0^2 y = 0,$$

$$\omega_0 = \sqrt{g / l},$$

$$\omega = \frac{4\nu}{D_p^{\ 2}}$$

Result of the equation:

$$y(t) = C_1 e^{-t(\omega + \sqrt{(\omega^2 - \omega_0^2)})} + C_2 e^{-t(\omega - \sqrt{(\omega^2 - \omega_0^2)})} + C_3$$

To simplify lets take y (0) =0 and $y(t \to \infty) = 0$, so we have $C_1 = -C_2 = -C$ and $C_3 = 0$.

$y(t) = 2C\, e^{-t\omega} \sinh\left(t\sqrt{(\omega^2 - \omega_0^2)}\right);$

We have to case:

1) $\omega > \omega_0$ => $y(t) = 2Ce^{-t\omega} \sinh\left(t\left|\sqrt{(\omega^2 - \omega_0^2}\right|\right)$ (sinh – hyperbolic sine)

2) $\omega \le \omega_0$ $y(t) = 2Ce^{-t\omega - i\pi/2} \sin\left(t\left|\sqrt{\omega^2 - \omega_0^2}\right|\right)$

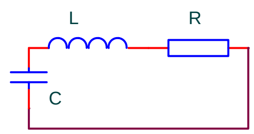
At the end of the pipe the diameter is D_v , the following substitution can be made

$\omega_0 = \sqrt{g / l}$ to $\omega_0 = \sqrt{\frac{g}{l}\frac{D_p^2}{D_V^2}}$.

Estimations with pipe $\ell = 30\,\mathrm{m}$ (100 feet) gives value $\omega_0 = 0.07$ and $\omega = 0.42$ when $D_p = 9.5$[mm] and $D_V = 77$[mm]. So we have $\omega > \omega_0$ an over-damped response of water circuit and no self resonance vibrations. So finally levels behavior could be fitted to an exponential equation:

$y(t) = Y_0 e^{-2\omega t} + y_0$, where y_0 - initial offset. (*)

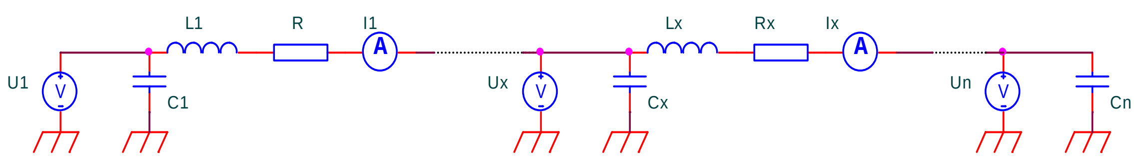
An analogy can be made to and LRC circuit with the lumped parameters as shown below.



Here:

$L = \dfrac{\ell}{\rho S_p}$, $C = \dfrac{\rho S_V}{g}$, $R = \dfrac{2\pi\nu \cdot \ell}{S_P^2}$, S_P - cross section area of pipe, S_c - cross section area of vessel.

For system from n level sensors $H_x = \dfrac{U_x}{g}$ and average of speed of water in the pipe $V_x = \dfrac{I_x}{\rho S_p}$ the electric model of the scheme represented is used:



The following Figures present measurements and results of a Full-Filled HLS system with lengths of 30 and 60 meters. The system contains two level sensors connected by polyethylene pipe with 12.7 mm (1/2 inch) outer diameter. Fitting gives values $\tau = 69.2$ sec to the 60 meter system and 36.6 sec to the 30 meters system. The dependence τ on length does not followed from the presented relation for ω. This question will be studied later. We can still use the analogue to the electric model.

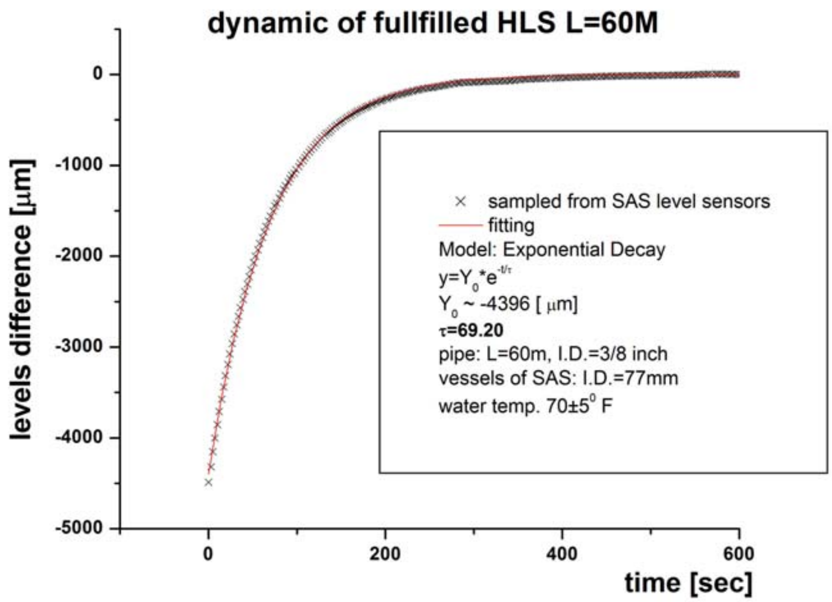


Figure 4 Over damping behavior of HLS with length 60M

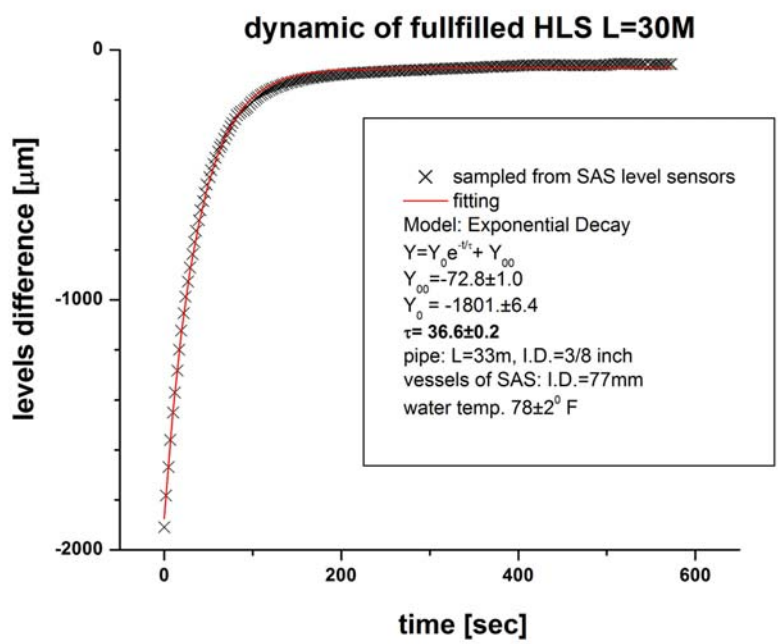


Figure 5 Over damping behavior of HLS with length 30M.

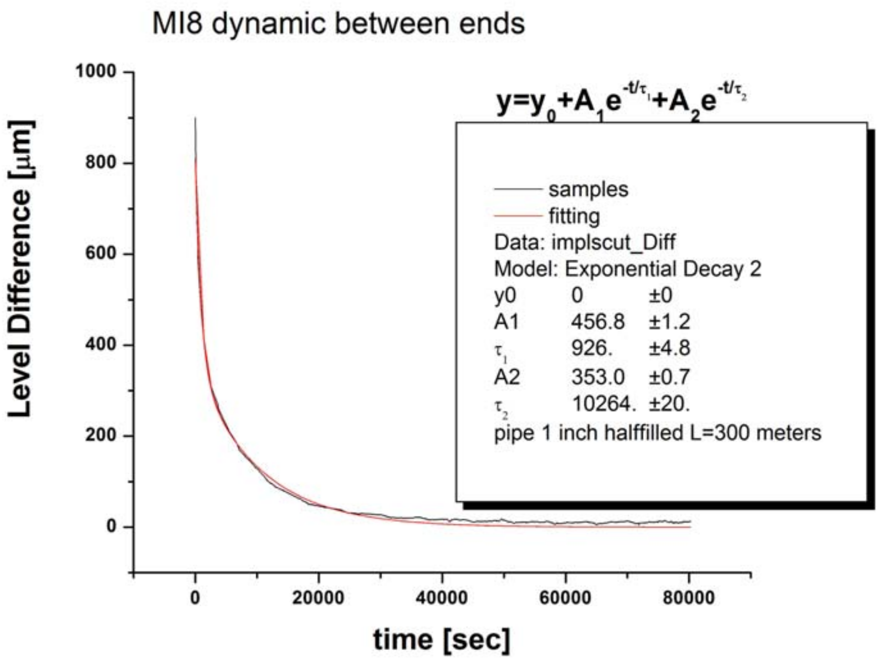


Figure 6 Dynamic example of half filled system.

Figure 6 presents the same fittings procedure for half filled tubes. The equation gives two different decay times: first is about 5 minutes, the second about 3 hours. A half filled HLS system more complicated in response time. In addition the pipe system has to be well supported exclude warping when water is added.

It is possible to model dynamic behavior of an HLS system as an LRC circuit, and to drawn corresponding analogies and numerical transformations. The problem is facilitated computer programs that can model electrical systems. To draw similar analogies of system with half filled pipes difficultly due to the presence of two-phase media.

4. Conclusions

- "Double tubed" full filled system for vertical alignments, are cost effective solution for high precision hydrostatic levelling system instead of half filled. Stabilizing temperature increases accuracy.
- A parametric model for a full-filled system is shown.
- Half filled system is more difficult to model but can be done.

5. Reference

[1] D.Martin, D.Roux, "Real time altimetric control by a hydrostatic leveling system", Proc. of II IWAA, DESY, Hamburg, 1990.
[2] W.Coosemans, F.Francia, "Vessels, pipes, water for precise alignments inside LEP", "Graviton" (Geneva, Switzerland), September 1994, p.14.
[3] A.Seryi, et al., "Long term stability study at FNAL and SLAC using BINP developed Hydrostatic level system", Proceedings of the 2003 Particle Accelerator Conference.

[4] A. Chupyra, M. Kondaurov, A. Medvedko, S. Singatulin, E. Shubin, "SAS family of hydrostatic level and tilt sensors for slow ground motion studies and precise alignment", IWAA2004, CERN, Geneva, 4-7 October 2004