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

S. Singatulin, J. Volk, V. Shiltsev
Fermilab, Batavia, IL 60510, USA
A. Chupyra, A. Medvedko, M. Kondaurov
Budker Institute, Novosibirsk 630090, Russia

Since 1998 several hydrostatic leveling system (HLS) systems have been installed in different locations on the Fermilab site. This work was in collaboration with Budker Institute and SLAC. All systems were either half-filled (HF) or full-filled system. Issues assembling HLS are covered in this article. Improved and cost-effective water system with temperature stabilized of water media, named double-tubed DT-FF, presented as an alternative to HF, and as next derivation of FF HLS, especially for interaction region of accelerators.

1. DOUBLE TUBED FULL FILLED (DTFF) HLS

With the increased requirements of accelerators alignment accuracy of hydrostatic leveling systems are used as a point of the space reference [1]. More and more of these systems are based on half filled water pipes [2]. Users rarely use or project systems based on full filled pipes. The main reason is uncertainties of measurements from the liquid circuit, due to the combination of both thermal gradients along circuit and liquid dilatation. Since water specific mass changes with temperature (except for water close to 4°C) and because temperature is not measured everywhere along the water circuit between communicating vessels, the measurement uncertainty Δz is sourced by all vertical parts of water pipes, as a consequence of the different temperature between these parts. The following picture shows variation of water density relatively to density on 4°C.

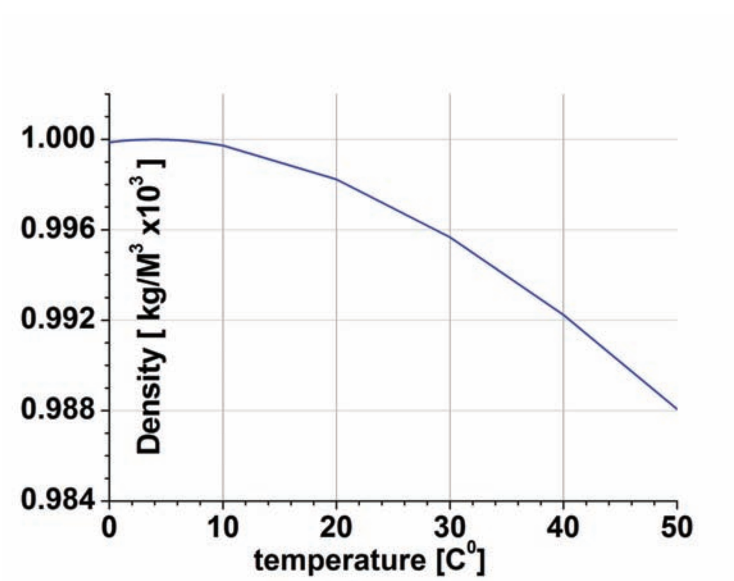


Figure 1. Water density

For example, at T=20°C a temperature difference of ΔT = 1°C between two vertical branches of water circle (vertical component amplitude h = 1 cm) induces Δz = 2μm (a vertical departure of water surface position in the two vessels. At Fermilab experience with half filled systems has given much information about the disadvantages and advantages of two different systems. In following Table 1 the author has tried to classify them.

Table 1

Properties	**Full Filled**	**Half Filled**	**Double Tubed Full Filled(suggested)**
Temperature stability	Depend from temperature	Excellent	Excellent
Material of tube	Cheaper, transparent Plastic	High cost Stainless tubes	Cheaper, 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

Double tube system uses two tubes with water and one tube with an air circuit. The first tube is for levelling measurements, the second tube paralleling the first tube has water circulating in it by means of a pump and is used to maintain a constant water temperature. In this way we exclude temperature gradients in water circuit. In addition the water could pass through the base of the pools to stabilize the sensors and electronics. As consequence of those two steps it is possible to realize high precision "double tubed" hydrostatic levelling system. Circulating water in second tube instead in original water tube excludes dynamic disturbing of water level and thereby receiving data from sensors instantly.

2. MI8 HLS – HALF-FILLED SYSTEM

There were many HLS system installed at Fermilab. One of them was mounted in tunnel MI8 [3] in 2001. The system consisting of 20 sensors SAS [4], located along a tunnel of Main Injector in section MI8 [3] for a total length of 300 meters . In this system transparent plastic pipes were used, with an internal diameter is 25.4 mm (one inch). The system also had a test device, allowing adding or removal of water. This device allowed managing the water level remotely by using RS485 serial card from PC under a programmed algorithm. The Test Device allows testing dynamic behavior and is very effective in testing system. Mechanics of TD for the system tests is represented in figure 2. Submersible Cylinder (7) is mounted on rod (6) and placed in tank (9) filled with water, which has one connection to tube line of the HLMS. Vertical position of the Cylinder is defined by rod bearing (5). Rod is moved by micrometer (4), which shifts on 1 mm per every turn of motor rotor (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 help of the platform tilting screws (8). All parts inside water tank are made from stainless steel materials. Water tank has additional hole on top for balancing air pressure inside and outside of tank.

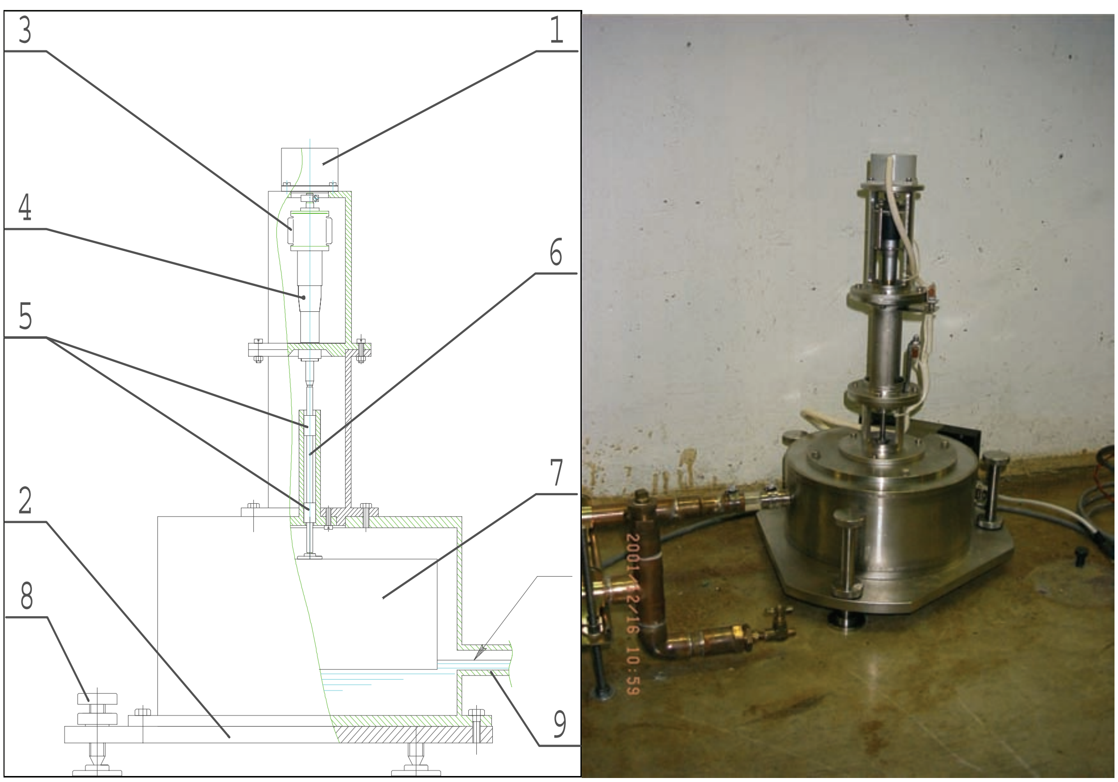


Figure 2. Test Device at SLAC

Figure 3 shows the dynamic reaction of levels, when mean level of water derived by removing from the one end of system close to sensor L0. HLS system had stabilized in gap +/- 10 micrometers just after 15 hours with shifting of mean level 100 micrometers.

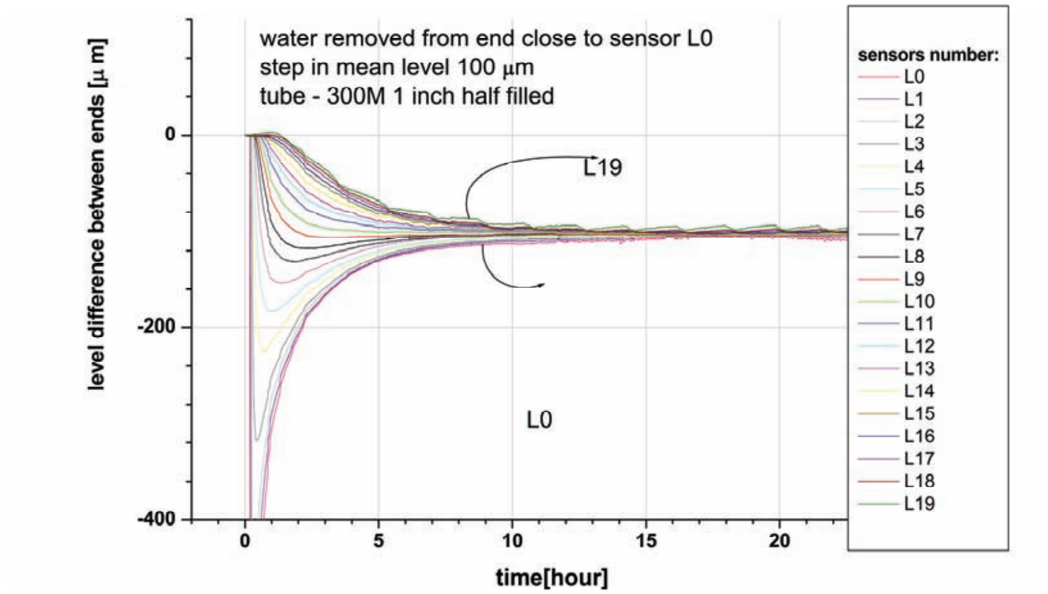


Figure 3. Step reaction HLS in MI8

3. MODELLING OF HLS

Many modern system need to be stabilized in real time in space and control positions by movers. Is it possible to predict the behavior of these systems? For vertical control very often used HLS system as sensor in feedback. We suggest simulating HLS to define in what frequency band HLS is applicable. Another advantage of modeling is to predicted behavior of system before construction of the system to exclude unforeseen circumstances and to avoid significant material charges. Modeling also helps to understand processes that occur in existing systems. Let's consider laminar flowing of a Newtonian incompressible viscous liquid (water) in a pipe in length ℓ in diameter $D_p < \ell$ in a gravity **g** with looking up ends (model of a simple level gauge). Forces present:

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

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.

Momentum balance is:

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

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

Since **y** means average in cross section, make substituting:

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

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

Using (2) give us equation:

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

In other form:

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

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

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

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

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

We have to case:

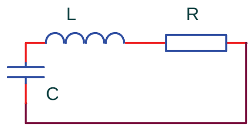
1) $\omega > \omega_0$ => $y(t) = 2Ce^{-t\omega} \sinh\left(t\left|\sqrt{(\omega^2 - \omega_0^2}\right|\right)$ (sinh – sine hyperbolic)

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

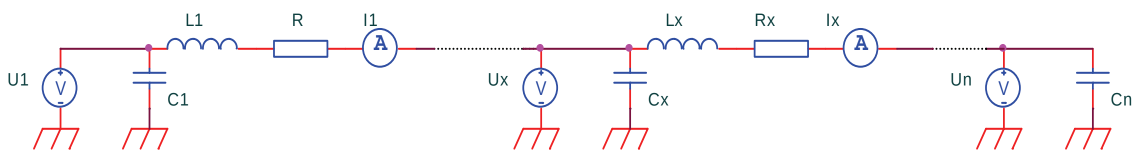
Since we have at the end of pipe vessels with other diameter D_V, we have to make additional substitution $\omega_0 = \sqrt{g/l}$ to $\omega_0 = \sqrt{\frac{g}{l}\frac{D_p^2}{D_V^2}}$.

Estimations with a pipe $\ell = 30$ m(100 foot's) gives value $\omega_0 = 0.07$ and $\omega = 0.044$ when D_p = 9.5[mm] and D_V = 77[mm]. If $\omega > \omega_0$ flow has over-damped response of water circuit and has no self resonance vibrations. So finally levels behavior look could be fitted with exponential equation: $y(t) = Y_1 e^{-\omega_1 \cdot t} + Y_2 e^{-\omega_2 \cdot t}$. (*)

To make an analogy in the resulting equations of an electric current I (U) circuits with connected inductance, resistance and capacitors it is possible to receive electric model (fig. below) with the lumped parameters.



Here:
$L = \frac{\rho\ell}{S_p}$, $C = \frac{S_V}{\rho g}$, $R = \frac{2\pi\nu\rho\ell}{S_P^2}$, S_P - cross section area of pipe, S_V - cross section area of vessel. The pressure difference ΔP is analogous to the U_x voltage, volume flow rate Φ is analogous to the current I. For system from n gauges with levels $H_x = \frac{U_x}{\rho g}$ and average of speed of water in a pipe $V_x = \frac{I_x}{S_p}$ the electric model of the scheme represented in figure is used:



On following pictures presented measurements and fitting result of fully filled HLS system with length 30 and 60 meters. The system contains two SAS level sensors connected by polyethylene pipe with 12.7 mm O.D. (1/2 inch O.D.) and length of 30 or 60 meters (100 or 200 feet). Fitting gives decrement values τ 30 and 98 seconds on pipes length 30m, 62 and 188 sec. - on length 60 meters. Proportional dependence τ from length is not followed from the presented above relation for ω .That is question for further study. Nevertheless we can use analogues with electric model.

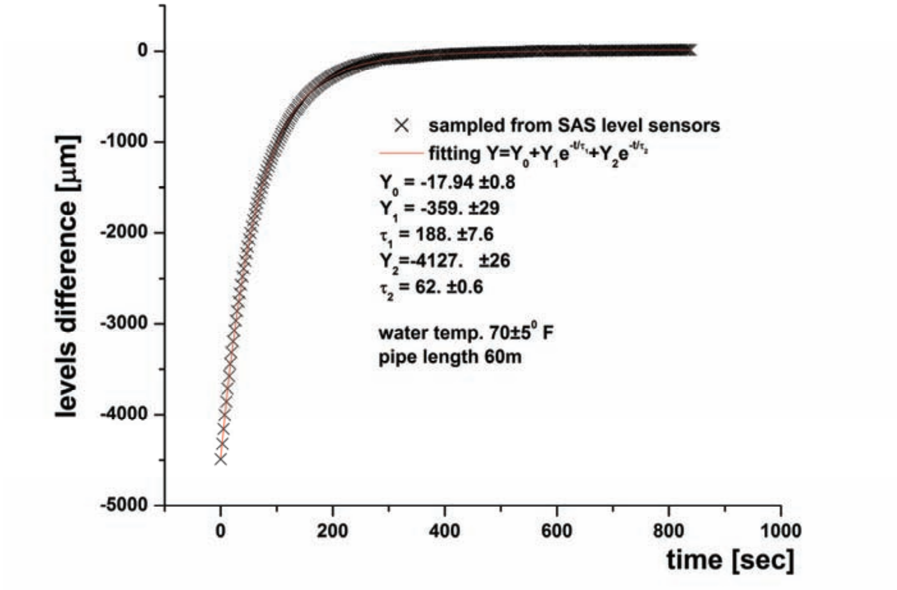


Figure 4. Over damping behavior of HLS with length 60M

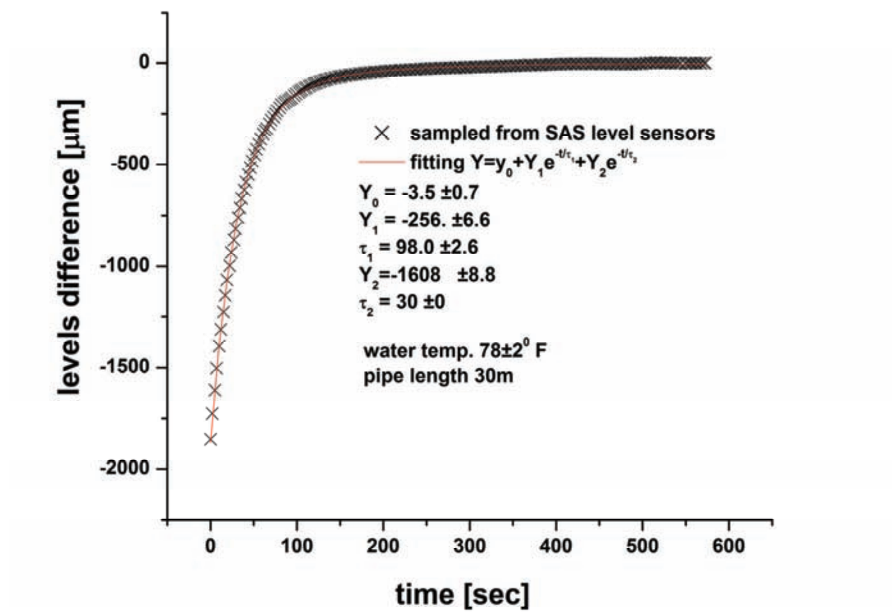


Figure 5. Over damping behavior of HLS with length 30M

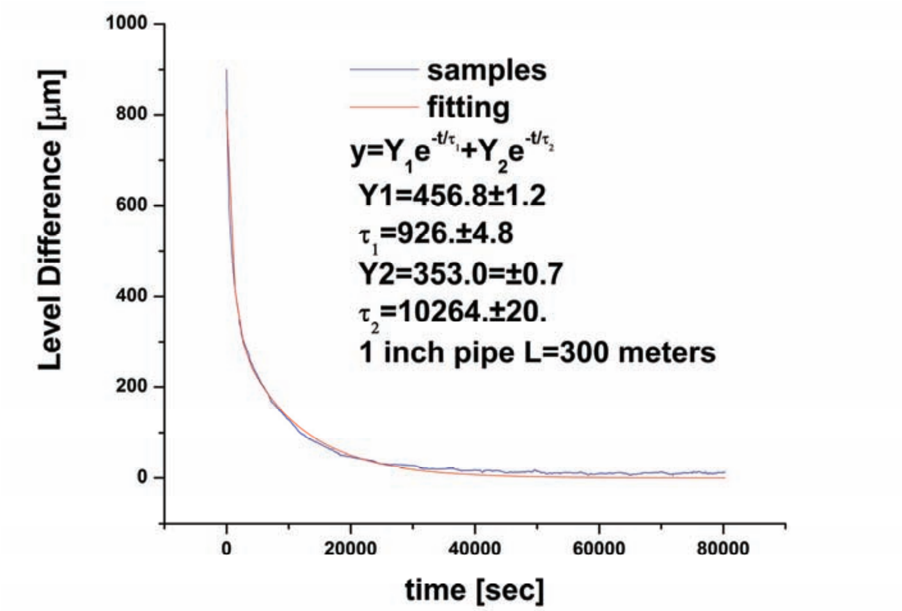


Figure 6. Dynamic example of half filled system

On Fig.6 presented the same fittings procedure for half filled tubes. This system has long setup time. Also fitting equation gives two essentially different decay times: first is about 5 minutes, second – 3 hours. Half filled HLS system are slowly in response and single pipe system have be to supported very well to exclude sag when water is put in the system.

Thus, it is possible to model complex HLS systems dynamic behavior as an electric system, drawing corresponding analogies and numerical transformations. The problem is facilitated also by the fact that many CAD systems have the capability to simulate behavior of passive and active elements. To draw similar analogies of system with half filled pipes is difficult enough since of presence two-phase media in pipes. Nevertheless it also is obviously possible.

Thus, having measured once parametrical values used pipes on unit of lengths and gauges itself on the test facilities stand, it is possible to model behavior HLS and more accurately to interpret measurements.

4. CONCLUSIONS

- We suggest "Double tubed" full filled system for vertical alignments, as cost effective solution for high precision hydrostatic levelling system instead of half filled. Accuracy results by the help stabilizing temperature in all system.
- The parametrical model, acceptable for full filled and double filled HLS is offered.
- Half filled HLS has higher time setup relatively to full filled.

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.