A Novel Approach to Improve Diverter Performance in Liquid Flow Calibration Facilities

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Abstract: *A diverting device (diverter) is an essential and error determining component part of a liquid flow calibration facility based upon a static gravimetric system with flying start and finish. The diverter timing error can be considerably reduced by the use of an angular encoding transducer in combination with an appropriate electronic and storage device. Further benefits in diverter performance can be obtained by an electric diverter actuator.*
Keywords: Liquid flow calibration, Fluid diverter, Time error correction, Electric diverter actuation

1 INTRODUCTION

High accuracy liquid flow calibration facilities are generally based upon static weighing gravimetric systems with flying start and finish [1]. Such a ***static weighing calibration facility*** generally comprises 3 fundamental component parts (see Figure 1):

- *flow generation system*: comprising storage tank, speed controlled pumping system, flow control system, which actuates the control valve, and optionally a constant head tank;
- *calibration lane:* piping system implementing defined flow conditions and incorporating the meter under test (MUT), i.e. the meter to be calibrated;
- *reference system:* precision balance with weighing tank and flow diverting device.

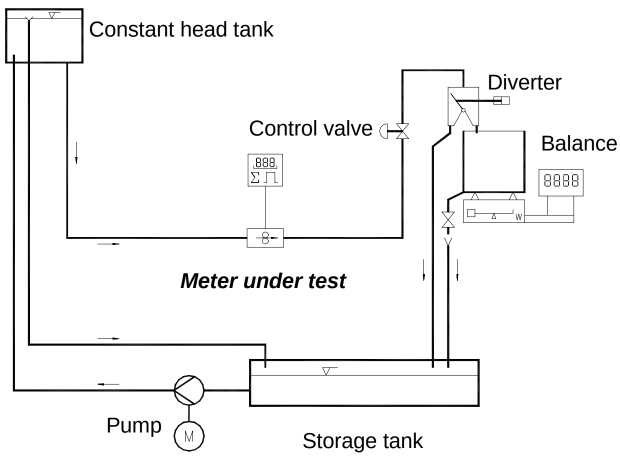

Figure 1. Schematic of a gravimetric liquid flow calibration facility

The *flow generation system* causes the liquid to pass through the calibration lane at a given and constant flow rate at which the meter under test is to be calibrated. The liquid flow rate Q_M is stabilized by a flow control system actuating a control valve, and a speed controlled pump system. As an additional means a constant head tank can be used as an option to provide a constant flow rate over the time through the measuring lane. The constant head tank improves the flow rate time constancy through the measuring lane where the meter under calibration is inserted into the fluid path.

Time constancy of the liquid flow rate during calibration is a strong requirement in order to improve diverter performance, i.e. to reduce the uncertainty of measurement of the respective calibration facility.

The *measuring lane* represents that part of the installation where the meter under calibration is installed within the pipe system, and whose main task is to implement optimum flow conditions for flowmeter operation, i.e. no swirls, a given and constant velocity profile of the streaming liquid. Therefore, a flow conditioner is often installed upstream of the flowmeter to avoid any flow disturbances that might affect the meter performance.

The *reference system* represents that part of the calibration facility in which, during the time period between $\mathbf{t_{10}}$ and $\mathbf{t_{40}}$ (see Figure 2), i.e. the collection time, a sample of the streaming liquid is directed into a tank whose contents can generally be determined in terms of volumetric or gravimetric units. In the case of a static weighing calibration facility this part of the system is realized by a weighing tank on a balance system.

In such a calibration assembly the diverting device represents a highly accuracy determining component part whose function is to direct the liquid flow, alternatively, either to the storage tank or to the weighing tank without disturbing the flow rate through the flowmeter under calibration.

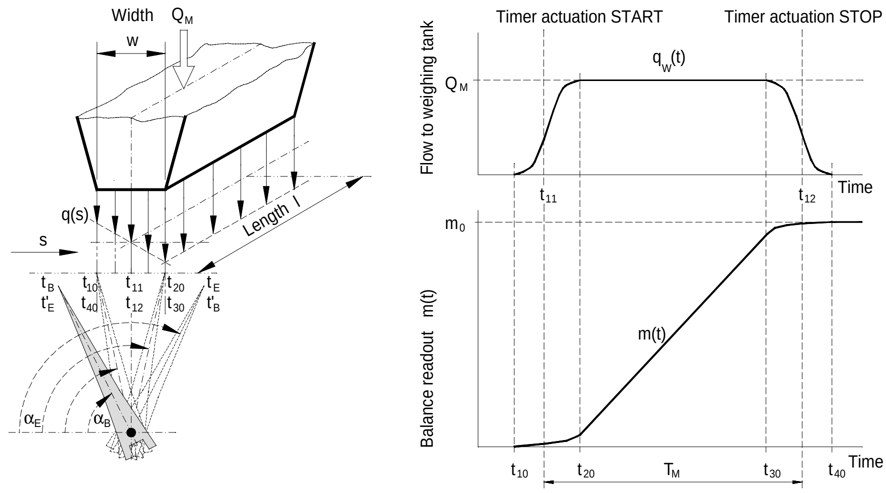

Figure 2. Principle of flow diversion

2 DIVERTER IMPACT ON CALIBRATION ERROR

The respective flow rate through a flowmeter can be considered as:

- *volumetric flow rate* and totalized volume through volume flowmeter:

$$\dot{V} \qquad \text{and} \qquad V = \int \dot{V}(t)dt \tag{1}$$

or:

- *mass flow rate* and totalized mass through mass flowmeter:

$$\dot{m} \qquad \text{and} \qquad m = \int \dot{m}(t)dt \tag{2}$$

The majority of flowmeters are volumetric flow rate metering devices (exceptions are true mass flow meters, such as Coriolis-type units). Calibrating such a type of flowmeter requires mass-to-volume conversion by additionally using a density meter continuously fed from the calibration liquid stream. This conversion must be taken into consideration in the definition of the measuring uncertainty budget of the calibration system.

For a totalizing volume flowmeter (the subject of the study described in this paper) the meter readout, when the calibration has been finished, is given as follows:

$$V_M \quad = \int_0^{T_M} \dot{V}(t) \cdot dt \tag{3}$$

In typical technical applications the procedure of time integration is represented by a pulse count from the flowmeter signal output accumulated by an electronic counter during the measuring time $\mathbf{T_M}$.

This measuring time is derived from dedicated positions of the diverting edge that are marked by position switches (see Figure 2) generating the gating signals for the electronic counter measuring $\mathbf{T_M}$.

This meter readout will be compared with the reference volume $\mathbf{V_{REF}}$ determined via mass to volume conversion from the balance readout $\mathbf{m_0}$ by application of the liquid density **ρ** :

$$V_{REF} = \frac{m_0}{\rho} \tag{4}$$

In order to minimize the diverter impact on the whole calibration system measuring uncertainty the duration of either traverses (determined by time differences $\mathbf{t_{20}}$ minus $\mathbf{t_{10}}$ and $\mathbf{t_{40}}$ minus $\mathbf{t_{30}}$, respectively) should be as short as possible, their absolute values being limited by the effective measuring time $\mathbf{T_M}$ of a calibration procedure.

The maximum velocity of traverse is limited to values above which the diverting edge would distort the liquid jet at the nozzle outlet, so that all geometrical assumptions concerning cross sectional flow area and the respective relations describing the diverting motion (which are being generally applied, and so in this paper) would no longer be valid. Practical values for the diverting times may range from some 50 ms to some 100 ms, depending on diverter size and actual flow rate.

Examples showing how the single component parts (net mass determination, liquid density metering, collection time, and others) of a high accuracy liquid flow calibration facility determine the total uncertainty of measurement of the calibration system are given in [2], [3], and[4].

With respect to the contribution of the diverter to the total uncertainty of measurement the error affecting factors of the diverting device in a liquid flow calibration facility can be grouped as follows:

- *Flow related factors of influence,* such as shape of the cross sectional flow area of the liquid jet at the nozzle outlet, non-constancy of local flow velocity along the path which the diverting edge is passing, splashing, and others [5].

- *Factor of influence* that is determined by the non-constancy of the diverter travel velocity when its edge is passing across the liquid stream in either direction.

- *Accuracy, adjustability, and stability* of the switching condition of the "proximity" switch that derives start and finish conditions of timing counters in flowmeter calibration.

The objective of this paper is to show appropriate measures to reduce function and performance degrading effects caused by factors of influence 2 and 3. Flow related factors of influence are treated in paper [5].

At PTB Braunschweig, Germany, a new high accuracy water flow test facility is presently under construction. This facility is intended to represent the national standard for mass and volumetric flow rate and flow related quantities like mass and volume of streaming water in the future.

Design work and first practical results, described here and in [5], were realized in the project aimed at designing, erecting, and establishing this new facility.

Special provisions were made, among other details, to implement high performance diverting devices with minimum impact on measurement uncertainty; first experimental results can be presented here.

3 MEASURES AND MEANS TO REDUCE DIVERTER TIMING ERROR

3.1 Improved Diverter Drive and Transition Motion Control

In PTB's new high accuracy water flow test facility, which is being realized at present time, special provisions were made that the diverter movement of traverse follows a given trajectory (see Figure 9a) most exactly, and that the timer actuation is obtained with maximum accuracy.

These two goals were accomplished by applying an electric diverter actuator and an angular encoder attached to the diverter pivot. Figure 3 shows the schematic side view of a diverting device developed as a prototype diverter for the new PTB water test facility (Figure 4). Flow related aspects of the diverter design (flow conditioning by appropriate piping design and shaping of the cross sectional flow area along the diverter feeding pipe and at the nozzle outlet, avoiding jet splashing) were discussed in detail in [5].

The local fluid velocity in the nozzle outlet stream may not exceed a maximum value to provide optimum flow conditions and to guarantee that the water jet has a rectangular-shaped cross sectional flow area in the region where the diverting edge is crossing. For this purpose the mechanical design of the diverter provides means to vary the width **w** of the cross sectional flow area (see Figures 2 and 3) by an electric drive actuator. The nozzle width can thus be adapted to the respective liquid flow rate $\mathbf{Q_M}$ so that the local flow velocity **q(s)** does not exceed a given value, say 4 m/s.

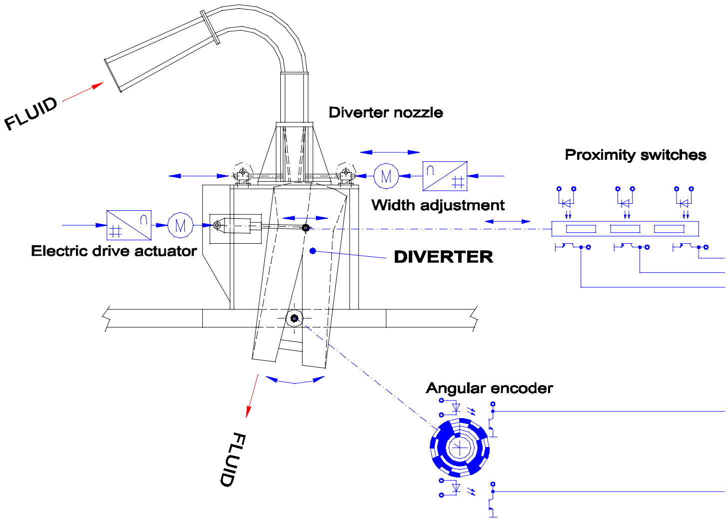

Figure 3. Diverter drive and motion control (schematic)

To achieve an improved diverting performance the new diverter design incorporates an electric drive actuator whose functions are controlled by a dedicated programmable logic controller (PLC) supervised by the process control system of the calibration plant.

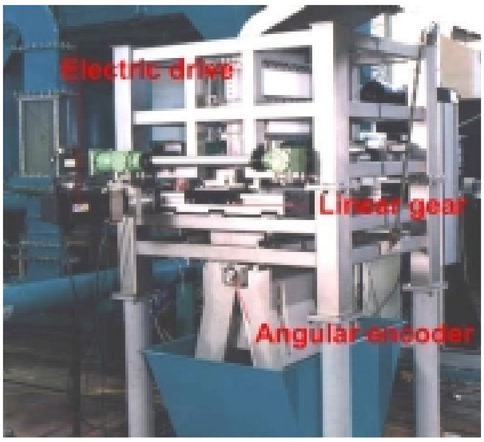

Figure 4. Diverter prototyp equipped with electric drive and PLC based motion control

The diverter traverse is thus an exactly position and velocity controlled and monitored motion, the whole traverse can be imagined as a series of a huge number of very precise single position steps exactly located at a given series of set-point values. This series of angular position set-points is the predefined trajectory of the diverter edge during fluid diversion. Parameters of this trajectory (phase of acceleration, velocity, deceleration, and others) can be adapted to achieve an optimum response behavior, for instance in the case of a non-ideal local fluid velocity distribution along the path of the diverting edge across the liquid jet (as indicated in Figure 2).

This outstanding diverter performance can be observed in Figures 9 a and b.

3.2 Measurement Subsystem to Acquire Diverter Transition Data and to Generate High Precision Timer Actuation

As shown in the schematic of Figure 3, there is a high precision angular encoder attached to the diverter pivot. On the basis of the digital encoder output signals a special embedded processor control and data acquisition unit provides high accuracy timer actuation and data acquisition functions. The acquired transition data serve for an improved approach to correct the diverter timing error through a special type of retrospective analysis of the diverter position-time trajectory during a measurement cycle of the calibration facility.

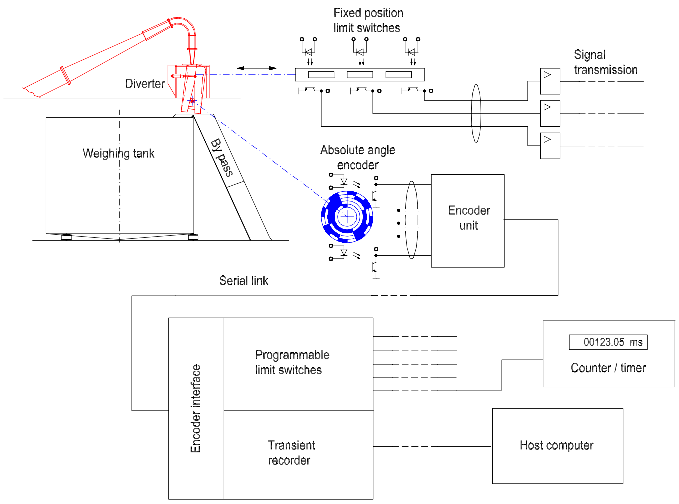

Figure 5. Programmable angular position acquisition system

The position-time trajectory is captured during either transition of the diverter and is analyzed in an off-line operating mode, using standard software tools such as spreadsheet programs. By an absolute angular encoder (Figure 5) a time series of angular positions is captured with a time resolution of 50 µs in a transient recorder.

After a measurement cycle the data stored in the memory of the transient recorder is transferred to a host computer over a standard interface (e.g. parallel port). As an additional benefit the transient recorder system has extended features to provide a number (e.g. eight) of programmable position switches, which may be compared with the conventional proximity switches as to their function, but with a numerically definable position. The angular encoder is linked to the transient recorder system via serial link using a proprietary protocol by the encoder manufacturer Heidenhain, Germany.

The encoder can deliver a maximum of 40,000 angular position data sets per second, its operational speed is slowed down to 20,000 data sets per second in the system presented here. The encoder angular resolution equals 19 bits for one full turn, which delivers 524,288 unique position points. Due to the limited angular movability of the diverter the usable resolution will be between 12,000 to 24,000 position increments, this will be about 14 bits.

The transient recorder itself will only be active during the traverses of the diverter. Start and stop commands to capture the angular data can be generated internally by setting angular thresholds to integrated programmable position switches marking the beginning and the end of the diverter movement. One series of data sets is thus captured during the opening phase of the diverter (see Figure 9: BALANCE position) and another series during the closing phase (BY-PASS position). An external trigger signal can be used if a special experiment requires different capture phases (Figure 6).

All data of the programmable switches, especially the angular thresholds, is transferred from the host computer to the transient recorder system via the host interface. The system controller - a dedicated microprocessor - programs the thresholds to the registers of the programmable position switches, controls the timing of the transient recorder for start and stop trigger signals and transfers the acquired data to the host computer for analysis purposes.

Time measurement is performed by storing time stamps at the beginning and the end of both of the opening and closing phase. These time stamps are generated internally by a free running clock with a resolution of 50 µs (the system clock). System timing is controlled by a crystal oscillator (master clock) from which all timing signals are derived.

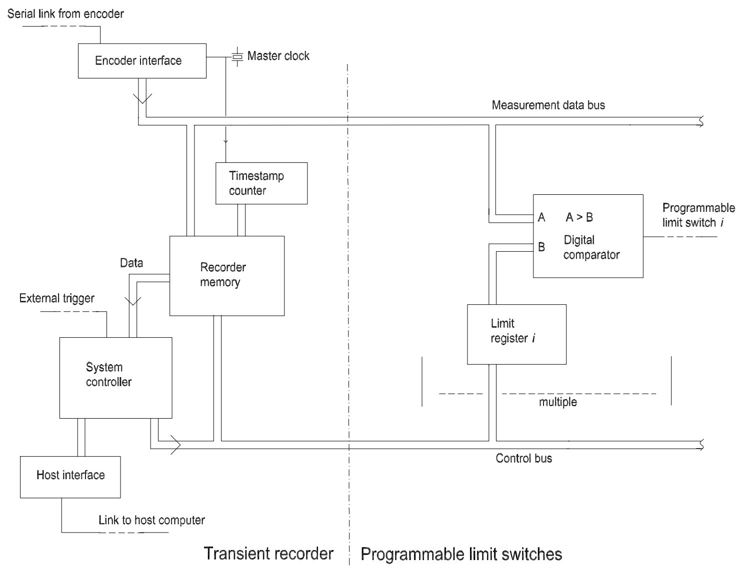

Figure 6. Function block diagram of a processor controlled position data recorder

After the measurement cycle, the two captured time series (diverter opening and closing, see Figures 9 a and b) of the angular position data sets are transferred together with the time stamps to the host computer. A first approach to calculate the time during which the liquid was directed towards the weighing tank will be a search for the angular position values equal to the mechanical switch point of the diverter during opening and closing. The relative time to the beginning of the position data capture may thus be calculated.

Together with the time stamps at the beginning of the two capture phases for opening and closing, the period of time $\mathbf{T_M}$ during which liquid has flown to the weighing tank is calculated. These time values are independent of the inaccuracy of proximity switches, of their positioning errors during set-up and of non-constancy of the diverter travelling velocity. The only errors come from timing deviations of the master clock (a crystal) and angular position deviations of the angular encoder and the bearing of the diverter.

4 DIVERTER TIMING ERROR CORRECTION

4.1 General Solution

In [2] an exact solution was given for the evaluation of the timing error of the diverter in a static weighing liquid flow calibration facility. This timing error results from improper alignment of the position switches dedicated to starting and stopping the liquid collection time interval.

Small quantity factors in the solution equation in [2] were neglected for practical purposes to lead to a simplified formula that has been applied to **ISO Standard 4185** (in [6], Method 1):

$$\Delta T_M = \frac{T_M}{N-1}\left[\frac{Q_0}{Q_N}\cdot\frac{\sum_{i=1}^{N}\Delta m_i \Big/ \sum_{i=1}^{N} T_i}{m_0/T_M} - 1\right] \tag{6}$$

The timing error correction is performed as follows:

Under static flow conditions, i.e. constant flow rate, constant fluid pressure and temperature, the weighing tank is filled during a single “burst” of flow (called standard run [6]) to full scale $\mathbf{m_0}$ (the balance output having been zeroed before); the metered time of flow is $\mathbf{T_M}$.

After emptying the weighing tank is filled again, now in a series of **N** constant flow bursts. As a result we now obtain a series of **N** increments Δm_i in balance readout, as well as the corresponding series of T_i, which represent the individual measurement periods of each single burst.

Applying these acquired quantities to Equation (6) determines the fractional time correction ΔT_M. The factor Q_0/Q_N takes into account any variation of flow rate. Q_0 represents the average flow rate during the single-burst filling of the weighing tank, Q_N being the average flow rate during the **N** bursts while the Δm_i are collected and accumulated in the weighing tank.

The result of this timing error correction is only valid for a given flow rate at which the above procedure has been performed. The procedure must be applied to all flow rates requiring calibration. The usual practice is that the determined fractional timing correction ΔT_M is simply added to T_M without performing any mechanical alignment of the position switches if it does not exceed a certain value.

4.2 Novel Approach for Minimizing Diverter Timing Error

In the "classic" approach for timing error correction [6] a single correction procedure delivers a single fractional time interval ΔT_M due to the fact that the only transition data information comprises counter/timer readout for T_M. Any mechanical alignment work with the timer actuating switches,

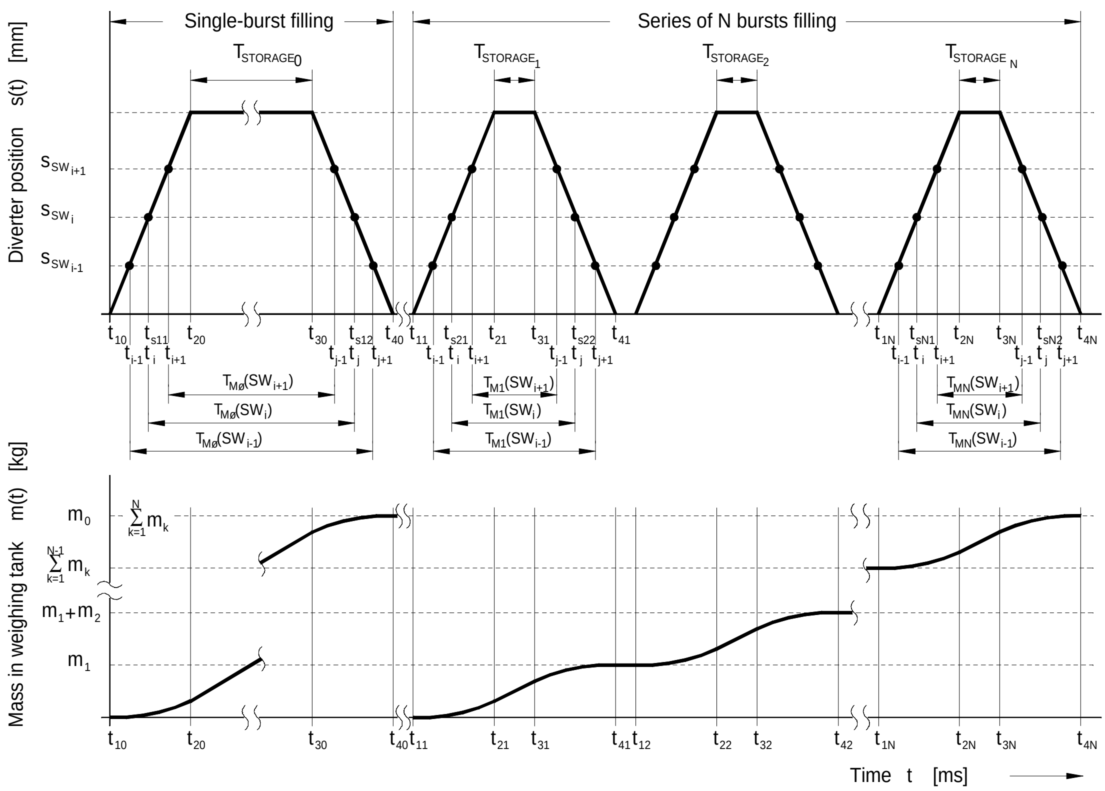

Figure 7. *Diverter timing error correction:* diverter transition responses and balance readouts

generally, implies a great uncertainty as to what the corresponding change of the time interval is with respect to a given local shift of the proximity switch. All mechanical alignment work requires time consuming verification of correctness and error-minimization, respectively.

If we use an angular encoder whose position output signals are fed to a transient recorder, as described above, to acquire the transient responses of the fluid diverter, we have a huge amount of information concerning the diverter's static and dynamic system behavior after a single correction procedure.

The diagram in Figure 7 represents all data obtained from a single correction procedure: diverter response data stored in the transient recorder and balance readout. When starting such an electronic switch "adjustment" we refer to initial conditions, represented by indices **i** , respectively **j** (see Figure 7):

- switching threshold $s_{SW\,i}$
- stored transient data (diverter transient positions) $s(t_i)$, $s(t_j)$
- $T_{STORAGE\ \ k}$, period of time in which the diverter is at rest at the BALANCE position; this time is determined by a counter/timer and is stored together with the transition data
- effective measurement time interval during the respective "burst" numbered by k :

$$T_{M\ k}\left(s_{SW\ i}\right) \ = \ (t_{2k} - t_{S\,k1}) + T_{STORAGE\quad k} + (t_{S\,k2} - t_{3k}) \tag{7}$$

Now one may apply $T_{M\ k}\left(s_{SW\ i}\right)$ in Equation (7) to Equation (6) to compute the fractional timing error correction of the diverter with $s_{SW\ i}$ being "adjusted" at an appropriate initial value. A good starting position of $s_{SW\ i}$ may be half the way from BY-PASS position to BALANCE position. On varying $s_{SW\ i}$ as an independent variable in the modified function of Equation (7) the timer actuation "adjustment" is simply reduced to solving a numerical problem, i.e. a minimum search starting from initial position:

$$\Delta T_M = f(s_{SW\ i}) \quad \Rightarrow \quad MINIMUM\,! \tag{8}$$

The resolution of $\mathbf{\Delta T_M}$ amounts to 50 µs, as this time-discrete solution is based upon transition data that were scanned at a rate of 1 data point per 50 µs.

To improve accuracy, the above approach can also be applied to the exact timing error equation given in [2].

Applying measured value interpolation in the given data sets acquired during calibration (Figure 7), the timing resolution achievable for $\mathbf{\Delta T_M}$ could be decreased to a magnitude as low as 10 µs. Even a systematic deviation of the flow characteristic of the diverter can be compensated for by applying off-line interpretation and analysis of the acquired time series data of the diverter's traverse.

As an essential benefit the approach presented here reveals:

- *Ease of diverter time error correction* by avoiding successive series of repeated steps: a single balance full scale run followed by a burst of a number of runs whose total mass equals the full scale run. In the "classic" way of time error correction the correctness of the switch alignment has to be verified by repeating the above procedure.

High-precision flow rate control must be implemented in a high-accuracy flow calibration facility to assure stability and repeatability, and so that $\mathbf{Q_0}$ and $\mathbf{Q_N}$ may be considered to be practically equal, and the respective quotient in Equation (6) becomes unity.

With PTB's new water flow test facility, special emphasis was laid upon high precision flow rate control [4] as one design goal to make time constancy of flow rate a factor of influence that may generally be neglected with respect to Equation (6).

5 EXPERIMENTAL RESULTS

5.1 Small-Size Diverter Prototype for a Down-Scaled Experimental Flow Calibration Facility

In order to prove the feasibility of the novel approach to fluid diverter timing error reduction, electrical drive actuation and angular encoder based transition data acquisition was implemented and tested with a down-scaled, small-size diverter prototype, as the water flow installation of the new PTB high flow rate calibration facility (up to 2,300 m^3/h) is not yet available.

This small-size calibration facility provides a maximum flow rate up to 10 m^3/h. The fluid diverter in use represents a retrofit design of an older diverter design in use with PTB for several years.

Improvements were gained by providing (besides several other design improvements) electric drive diverter actuation and addition of an angular encoder to the diverter set-up (see Figure 7).

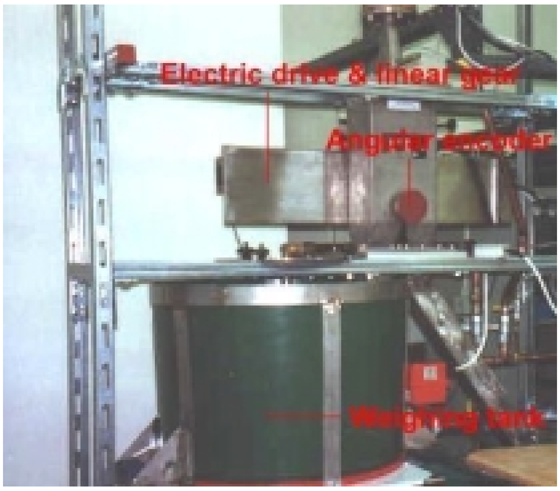

Figure 8. Smaller size diverter prototype
($Q_{max} = 10\ m^3/h$)

The tests of the new design components have shown excellent function performance, later proven by the real-sized diverter prototype for PTB's new test facility. Design details follow the functional principle shown in Figure 3.

The excellent time responses achieved are comparable to those in Figures 9 a and b and the diverter timing error correction based upon the above described approach has been proven to be feasible.

5.2 Real-Sized Diverter Prototype for New PTB Water Flow Test Facility

The new PTB water test facility will comprise two different-sized calibration lanes (DN 150 and DN 400) which can, alternatively, feed a calibration flow to 3 weighing systems (30 tons, 3 tons, and 300 kg). Each lane is equipped with an appropriate fluid diverting device. The choice of the appropriately sized weighing system thus provides optimum mass measurement at a given flow rate, the measurement time being optimized for a low diverter timing error.

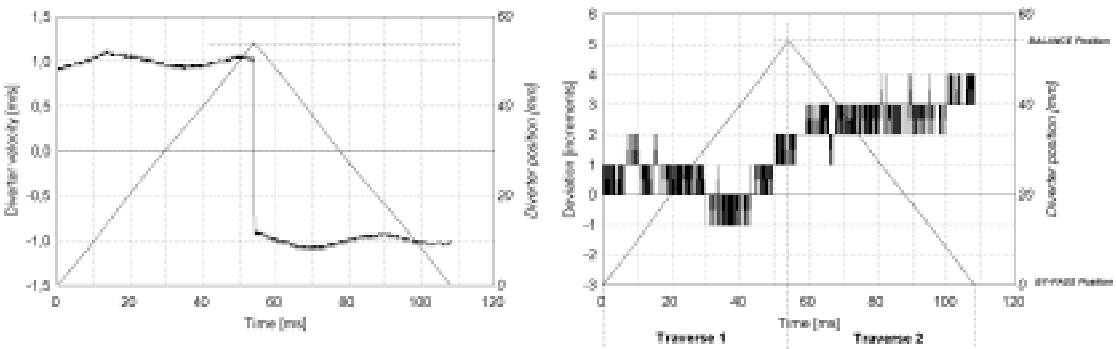

Figure 9. Diverter transition response
a) Velocity response
b) Position error when comparing two succeeding diverter travels
(total path length amounts to 11 555 increments, representing 54.1 mm)

The medium-sized diverter (with the 3 tons balance) was implemented as a first prototype (see Figure 4) for study purposes. Besides other aspects (e.g. optimum flow conditioning in the diverter piping system, and other flow related problems [5]), a special design goal was to implement an electric actuator, providing driving power which matches the greater forces of inertia of a real-sized diverter as well as the impact forces of a water jet at a flow rate of 100 m^3/h and greater.

Repeated experiments have shown (Figure 9 b) that over the diverter traverse there was a deviation not exceeding 3 increments in a time sequence of succeeding diversions. The total path length of a single diversion comprised some 11,500 increments at an operating flow rate up to around 100 m^3/h.

So these experiences acquired with the small-sized as well as with the real-sized diverters are essential preconditions to extrapolate to a larger-size diverter design that is part of PTB's new water calibration facility at flow rates up to 2,100 m^3/h [4].

6 CONCLUSIONS AND FINAL REMARKS

The provision of an angular position encoding device in combination with an appropriate electronic circuitry that allows the diverter switching positions (threshold of START or STOP pulse generation) to be adjusted electronically enhances accuracy and switching threshold stability, avoiding mechanical alignment work and other drawbacks.

By the use of an encoder and a combined transient recorder and digital comparator assembly the timing error correction problem is simply reduced to a non-linear algebraic equation solving problem, based upon a single set of measurement data. The result of this equation solving process is a number or (digital) value that represents the switching threshold of the START and STOP detectors of the diverter.

This numerical value can be easily transferred to and stored in an comparator register storage of the diverter electronic unit. The correction of the diverter timing error has thus been accomplished without requiring further mechanical calibration and alignment work or additional verification measurements.

Finally, it is worth mentioning that the performance of older diverter designs in existing calibration facilities can be tremendously enhanced with respect to their diverting and metering properties by retro-fitting an electric actuator and an angular encoding system.

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