

**DYNAMIC WEIGHING**  
**- IMPROVEMENTS IN GRAVIMETRIC LIQUID FLOWMETER**  
**CALIBRATION**  
**The 5<sup>th</sup> International Symposium on Fluid Flow Measurement**

*Dr. Rainer Engel, PTB Braunschweig, Germany*

**Introduction**

In fabricating flowmeters, the meter's calibration is its final and accuracy determining step that comprises a great time consumption relative to its completion from its single component parts. Thus calibration (unless the respective time of calibration for a flow meter is not minimized) may represent a relevant contribution to fabrication costs.

High-accuracy liquid flow calibration facilities are generally based upon static weighing gravimetric systems with flying start and finish. Even due to the fact that industrial liquid flow calibration facilities are successfully utilizing dynamic weighing, they still are being estimated to be less accurate than static weighing calibration systems.

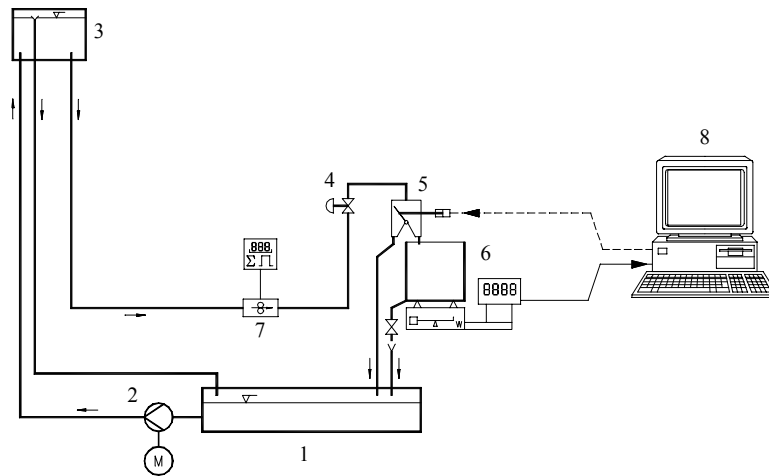
In international standards, static weighing has been preferred instead of dynamic weighing due to its estimated higher accuracy. This estimation has been based upon a rough mechanical model of an one-beam scale. The state of the art in the field of dynamic weighing liquid flow calibration, charging from the international standards, is still being represented by a theoretical foundation dating back about 40 years (1).

**Dynamic Weighing Flow Calibrators**

More or less recent developments and achievements in computer-based data acquisition, data processing algorithms, technical system modeling, and computer performance using powerful simulation software provided the possibility to design and build higher-accuracy dynamic weighing calibration facilities. Owing to these developments, we can distinguish two typical **types or variants of dynamic weighing calibrators**:

- 1) The "classic" ***mechanical calibrator*** based upon a lever scale whose calibration value is represented by two statuses of lever equilibrium and timer actuation periods, with the following drawbacks in performance: *change in impact force* of falling liquid; *change in delay time* when the weigh beam is moving from its rest position up to the timer actuation lever position.
- 2) The non-deflecting indication metering device (without any movable components serving for indication purposes) applying ***electronic load-cells***.

**Figure 1** depicts the principle of the setup of a liquid flow calibration facility that can be applied for dynamic weighing calibration, with a "diverting" device (of any type or design) "simply" being used to start and stop filling the weighing tank. The figure shows the general setup of a gravimetric flow calibrator, disregarding what the single component parts are realized like, e.g. a beam scale or electronic load-cell balance, i.e. "classic" lever balance or latest-design digital-readout balance.



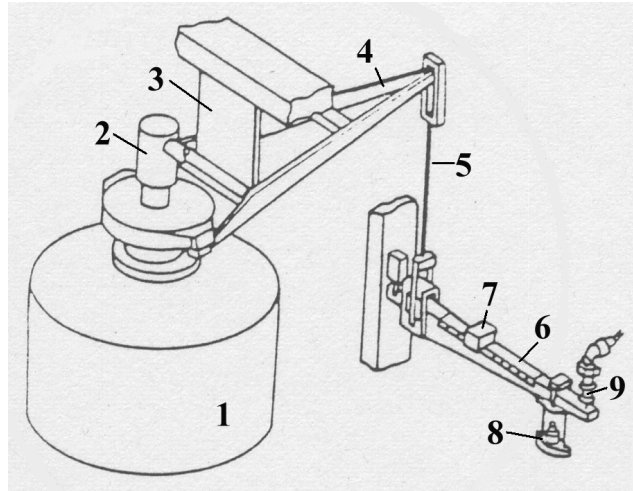
**Figure 1.** Liquid flow calibration rig with "dynamic" balance readout  
 1) Reservoir, 2) Pump(s), 3) Constant head tank, 4) Flow control valve, 5) "Diverting" device, 6) Balance with digital signal output, 7) Meter under calibration, 8) Data acquisition and control PC

### ***The "Classic" Mechanical Calibrator - Lever Balance***

The "classic" mechanical gravimetric liquid flow calibrator is generally based upon a hydraulic circuit as shown in Figure 1 and a lever scale with a weigh tank as a gravimetric reference (3). **Figure 2** shows the principle setup of a compound beam weighing system as it is used in a commercially available dynamic weighing calibrator (3).

A calibration run is started by closing a dump valve in the bottom part of the weigh tank (as it is used in this individual design instead of using a fluid diverting device in the feeding pipe section to the weigh tank) with the fluid flow rate having been adjusted and stabilized before at a value given by the calibration task. From that moment the weighing system collects and weighs a predetermined weigh increment of test liquid that has passed through the flowmeter to be calibrated. After this preparation running operation before test, two cycles of calibration are performed to determine the flow rate through the flowmeter under test:

- 1) ***Preliminary fill*** or ***Tare cycle***: This cycle is started in the moment when a tare weight is placed on the weight pan (**Fig. 2.**: item 7) with the dump valve having been closed and resetting the timer/counter before. With the weigh tank being filled, the weight pan rises, tripping the timer actuator (**Fig. 2.**: item 9; **Figures 3a** and **b**: item 1) and thus the electronic counting in milliseconds (START of measurement time  $T_{Meas}$ ) is started when the preliminary fill in the tank is balanced out by the tare weight.
- 2) ***Weighing cycle*** (Measurement time): This cycle follows immediately after the tare cycle and is continued as one of the precision weights (whose magnitude in mass  $m_{Weight}$  is suitable to deliver an appropriate value of measurement time at a given flow rate) is placed on the weight pan, deflecting the balance beam again. With the weigh tank filling, the weight pan (with precision weight on it) rises and, again trips the timer actuator (FINISH of measurement time  $T_{Meas}$ ).



**Figure 2.** Compound beam weighing system  
(COX Instrument, Bensalem, PA, USA)  
1) Weighing tank, 2) Fluid inlet, 3) Suspension assembly,  
4) Weigh beam, 5) Link rod, 6) Tare beam, 7) Tare weight,  
8) Weight pan, 9) Proximity switch (timer actuation)

The measurement time which the determination of fluid flow rate  $\dot{m}$  and flowmeter pulse count relies on is “simply” dedicated to  $T_{Meas}$  that has been metered between timer actuation in preliminary filling and weighing cycles, ignoring that there are varying delays in either measurement conditions:

$$\dot{m} = \frac{m_{Weight}}{T_{Meas}} \quad (\text{in kg/s}) \quad (2)$$

The variation in delay time is caused by the increasing fluid mass collected in the weigh tank (1). Due to the presence of varying delay times the actual fluid flow rate  $\dot{m}^*$  has to be calculated as follows:

$$\dot{m}^* = \frac{m_{Weight}}{T_{Meas}^* (\Delta t_{Delay})} \quad (3)$$

**Accuracy:** The calibration accuracy attainable when using this type of a dynamic weighing flow calibrator is determined by the precision of the weighing system (i.e. calibration accuracy with precision weights under steady-state conditions) and of the electronic devices for measuring time and counting pulses. Additionally, you have to take into account a varying delay time as described above.

With practical applications, the problem arises to quantify (i.e. to measure) the varying switching delay times of the preliminary fill and weigh cycles. The term  $T_{Meas}^* (\Delta t_{Delay})$  in **Equation 1** is to indicate that the measurement time  $T_{Meas}^*$  incorporates a varying time delay  $\Delta t_{Delay}$  between tare and measurement cycles.

### **Electronic Balances in Gravimetric Flow Calibrators**

A tremendous improvement in gravimetric liquid flow calibration was gained with the utilization of electronic balances (as shown in **Fig. 1**) substituting mechanic beam scales with all their disadvantages.

Generally, two transducer principles are in use with gravimetric flow calibrators:

- a) *strain-gauge force transducers* (i.e. direct-signal output)

- b) *weighing cell based upon electromagnetic force compensation* (that keeps a lever balance in equilibrium in case the input force varies in magnitude)

It should be mentioned that in PTP's new water flow calibration facility (6), three different-sized weighing systems were installed that incorporate dual-type balances, i.e. in each weighing system both type a) and type b) force transducers were combined as a functional unit. These dual-balance systems were realized in order to benefit from the advantageous properties of either type of force metering system that can be summarized as follows:

- *fast dynamic response of strain-gauge transducers* (that makes them very suitable for dynamic weighing applications)
- *long term stability and good measurement reproducibility of electromagnetic force compensation transducers*

As a matter of fact electronic balances are force-metering transducers. In a gravimetric flow calibrator they are sensing forces that are caused by the mass of the collected water under the influence of earth's gravity and by the motion of the water when falling or streaming into the weighing tank. The signal that is delivered by the weighing cell contains components resulting from both sources of influence.

Only in case of static weighing, i.e. when the balance's transition process has reached its final steady state, the balance readout represents the fluid mass collected by the calibrator during the measurement time.

## Measures to Improve the Performance of Dynamic Weighing Flow Calibrators

### *Mechanical lever balance as a deflecting metering instrument: Time correction (4)*

In order to compensate for the erroneous influence of inertia effects, the delay time of the beam's motion from its deflected starting position up to the equilibrium positions where the timer is activated during the tare cycle and the weighing cycle, respectively, provisions were made to meter the travelling time of scale beam from starting (i.e. being at rest) to the actuator's position (i.e. being in a motion under acceleration by increasing weigh force). For this purpose, additionally to the "standard" proximity switch 1 (see **Fig. 1**) a supplementary proximity switch 2 has been attached beside the calibrator's scale beam to



**a)**  
**Figure 3.** Compound beam weighing system  
*a) Detail view of tare beam (with "standard" proximity switch 1 only)*  
*b) Tare beam with additional zero position proximity switch 2*  
(reproduced with permission of KEM Küppers Elektromechanik GmbH, Karlsfeld, Germany)

detect when the scale beam is leaving its starting position. Utilizing this additional position switch facilitates to measure delay times  $\Delta t_{Tare}$  and  $\Delta t_{Weigh}$ , respectively (see **Table 1**).

**Table 1.** Delay times of a beam scale flow calibrator (4)

Flow rate (kg/min)	Weigh mass (lbs)	$T_{Meas}$ (s)	$\Delta t_{Tare}$ (ms)	$\Delta t_{Weigh}$ (ms)	$\Delta t_{Delay}$ (ms)	Relative deviation (%)
100	200	54,727	1,83	4,72	2,89	0,0053
	400	109,604	2,90	6,93	4,03	0,0037
	600	164,540	4,90	12,42	7,52	0,0046
500	200	10,909	1,51	2,56	1,05	0,0096
	400	21,814	1,74	3,28	1,54	0,0071
	600	32,744	1,89	4,48	2,59	0,0079
1000	400	11,169	1,89	3,20	1,31	0,0117
	600	16,732	2,06	4,33	2,27	0,0136

(All values are average values over 10 runs)

Measurement results from investigations with a dual beam weighing system of a flow calibrator (3), i.e. time delay error due to varying inertia, are presented in **Table 1**.

The measurement and computer-based supervision of delay time  $\Delta t_{Delay}$  provide an indicator concerning the balance's accurate working. On the other hand, the determination of this quantity is a pre-condition to establish a more detailed mathematical model of the measurement process with the aim to improve the measurement uncertainty that can be dedicated to an accredited calibration facility instead of making a (more or less) worst-case assumption of uncertainty according to (1,2).

**Further improvements** can be achieved in applying a continuously metering distance sensor instead of a discrete position switch, as the reproducibility of the scale beam's transition can be measured and supervised more accurately for quality assurance purposes.

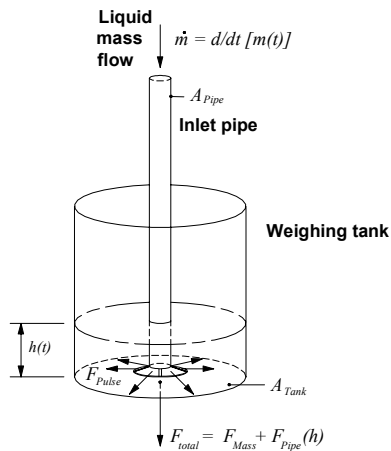
### ***Dynamic Weighing Flow Calibrators with Electronic Load-Cell Balance***

Another approach to improve dynamic weighing method with flow calibrators is to provide measures that avoid or compensate for erroneous influences resulting from varying impact forces (5) or mass inertia, respectively.

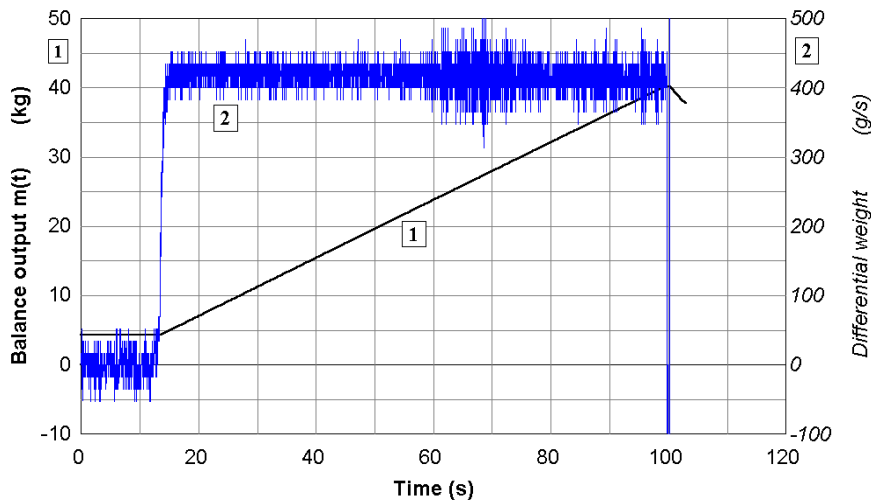
Electronic load or force transducers based upon strain-gauge sensors or electrodynamic force-compensation cells represent non-deflecting force-metering devices that do not imply drawbacks resulting from varying mass inertia, though their limited-bandwidth dynamic response behavior is to be taken into account as it will be shown in the main chapter to follow.

In (5) they have shown a design of a dynamic weighing calibrator, whose main goal it is to avoid impact forces of the water stream fed to the weighing tank. The basic principle is depicted in **Figure 4a**. So the impact force acting in vertical direction is compensated for (at least theoretically) by applying a deflecting plate that directs the incoming vertical fluid stream into horizontal direction. That deflecting plate is tightly attached to the inlet pipe, directly in front of its vertical outlet to the weighing tank.

**Figure 4b** shows a practical design of a dynamic weighing calibrator that relies on the principle described above. The accuracy of the dynamic balance has been proven to be as low as 0.05 %. As an example, the accurate performance, i.e. constancy of flow rate, is demonstrated in **Figure 5**.



**Figure 4.** Gravimetric reference with immersed inlet pipe and flow deflecting plate  
*a) Principle of function*  
*b) 40-kg balance of a dynamic weighing calibrator*  
 (Courtesy of Rota Yokogawa GmbH, Wehr, Germany)



**Figure 5.** Dynamic response of balance output signal at a mass flow rate of 1500 kg/h  
*1) Balance output signal  $m(t)$*   
*2) Slope of  $m(t)$*   
 (Courtesy of Rota Yokogawa GmbH, Germany)

**Figure 5** reveals that the slope of the balance output signal  $m(t)$  (curve 1) is constant, what is proven by curve 2, which represents the differential weight or mass flow rate  $\dot{m}(t)$ . As indicated in **Figure 4a**, the mass (or exactly the forces) measured by the balance amounts to:

$$F_{total} = F_{Mass} + F_{Pipe} \quad (3)$$

$F_{Pipe}$  describes the interfering influence of the feeding pipe immersed into the liquid. This force is proportional to the liquid level  $h(t)$  in the weighing tank, so it can be easily compensated for by the data acquisition device or computer.

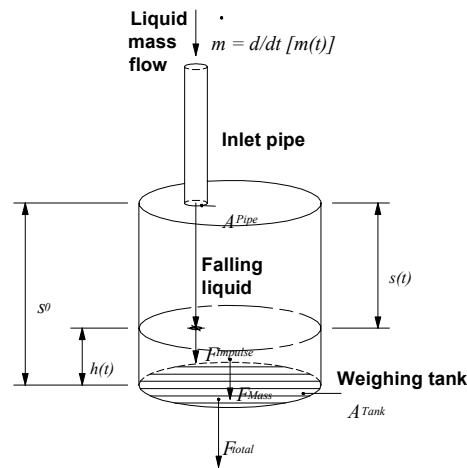
An **obvious drawback** and an accuracy limiting factor of this working principle is that the increasing fluid level within the tank causes an increasing counter pressure to the flow through calibration line and test meter, respectively, so that an active flow regulating facility is to be applied as dynamic flow calibration requires a constant magnitude in flow rate. But curve 2 in **Figure 5** proves practical feasibility of active flow rate control for a high calibration accuracy in industrial application.

Further improvements in accuracy of dynamic calibrators are definitely attainable by the utilization of a model-based approach as it will be described in the following main chapter.

## Model-Based Dynamic-Weighing Flow Calibrators

### Functional principle

For the purpose to design and to construct high-resolution static weighing systems for PTB's new water calibration facility (6), dedicated investigations and performance tests with an 1.5-tons weighing system (PTB's water calibration facility at Berlin location) had been performed to find an optimum setup for the balances. During this experimental work, it revealed that an electronic weighing system can be utilized both for static weighing and for dynamic weighing flow calibrators with a high accuracy performance. But in case it will be used as a dynamic weighing calibrator, we need essential information about the system's static and dynamic response behavior when the test fluid is filled into the weighing tank.



**Figure 6.** Gravimetric reference with freely falling inlet flow

This situation is roughly demonstrated by **Figure 6** and it can be described by **Equations 4** through **8**. The liquid input flow  $\dot{m}$  is passing through the inlet pipe and the average velocity over the pipe's cross section  $A_{Pipe}$  amounts to  $\bar{v}_0$ . After having left the inlet pipe the freely falling liquid endures an acceleration in the earth's gravitational field, so that the resulting impact velocity  $v(t)$  amounts to:

$$v(t) = \sqrt{v_0^2 + 2g \cdot s(t)} \quad (4)$$

As the liquid level  $h(t)$  increases during the calibration run, the fall height  $s(t)$  decreases (see **Fig. 6**). And so we obtain for the impact velocity as a function of time:

$$v(t) = \sqrt{v_0^2 + 2g \left( s_0 - \frac{\dot{m}_0}{\rho_{Liquid} \cdot A_{Tank}} t \right)} \quad (5)$$

The forces that are detected and indicated by the electronic balance (i.e. exactly by the force metering system) comprise the above impact force of the falling liquid, the weight force of the liquid collected, and the buoyancy force that equals to the mass of air displaced by the liquid in the tank:

$$F_{total} = F_{Mass} + F_{Impulse} + F_{Buoyancy} \quad (6)$$

For reasons of simplification, in the further consideration the effect of air buoyancy will be neglected. Assuming that the falling liquid's impact velocity is reduced to zero in the very moment when it hits the surface in the tank (bottom plate or liquid surface), the impact force can be calculated, approximately, as follows:

$$F_{Impulse}(t) \approx \dot{m}_0 \cdot \Delta v(t) \quad , \quad (7a)$$

with  $\Delta v(t) = v(t) \quad (7b)$

Combining **Equations 5** through **7** we obtain as the resulting force signal at the balance's output:

$$F_{Balance}(t) = \dot{m}_0 t + \sqrt{v_0^2 + 2g \cdot s_0 - \frac{2g \cdot \dot{m}_0}{\rho_{Liquid} \cdot A_{Tank}} t} \quad (8)$$

After a rearrangement of **Equation 8** we can expand the root expression into a Taylor series (8) comprising linear and quadratic terms of  $t$ :

$$F_{Balance} \approx \dot{m}_0 t + \sqrt{C_0} \left[ 1 + \frac{1}{2} \cdot \frac{C_1}{C_0} t - \frac{1}{8} \cdot \left( \frac{C_1}{C_0} \right)^2 t^2 \right] \quad , \quad (9)$$

with:

$$C_0 = v_0^2 + 2g \cdot s_0 \quad \text{and} \quad (9a)$$

$$C_1 = -\frac{2g \cdot \dot{m}_0}{\rho_{Liquid} \cdot A_{Tank}} \quad (9b)$$

Applying generalized terms to **Equation 9**, we obtain as the balance output signal:

$$F_{Balance} = b_0 + b_1 t + b_2 t^2 \quad , \quad (10)$$

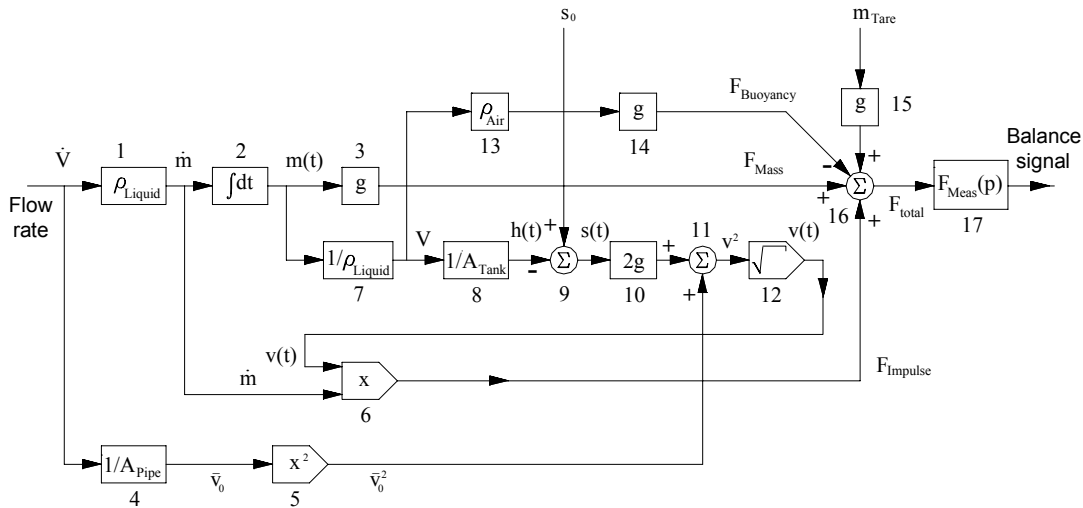
with the polynomial coefficients  $b_0$  through  $b_2$  describing the functional influence of constant flow rate  $\dot{m}_0$  and the balance's design parameters (see **Fig. 6**.) on the time response functionality of the weighing system.

The measurement results from the experimental investigations mentioned above have shown that a series expansion comprising linear and quadratic elements reveals to be exact enough for practical purposes. Comparisons between coefficients in **Equation 10** and those received from experimental investigations applying regression method on the balance output signal while filling the weighing tank facilitate to determine flow rate  $\dot{m}_0$ .

### ***Model of the Weighing Tank's Filling Process***

Instead of using an approximation function according to **Equation 9**, we can create a function block diagram (7) that describes - more or less exactly - the time responses of all those state variables whose

actions can be measured by the force-metering system, which we call dynamic weighing system. This function block and signal flow diagram shows the interrelations between the state variables of the weighing system (see **Fig. 6**) and of the balance output signal, which are described by **Equations 4** through **8**. The output signal, i.e. the digital balance readout, is the system's reaction on the input signal  $\dot{V}$  that results in the summed total force  $F_{total}$ . This signal is "shaped" by the delay or bandwidth-limiting transmission properties of the force-metering device or measurement system, which is symbolized in **Figure 7** by the Laplace transform (8) of the meter's transfer function  $F_{Meas}(p)$  (**Fig. 7**: function block 17).



**Figure 7.** Signal flow diagram of dynamic weighing process

The system model of the balance, which is represented by the above function block diagram, comprises one essential simplification in the description of the impact force (**Fig. 7**: function block 6). The same simplification or assumption was already made when we derived **Equation 8**. As to an erroneous influence of the above simplification, we can state that there is no "negative" effect on the accuracy of the process modeling unless the process conditions do not vary with the liquid level increasing in the tank.

To estimate whether there is a dominating influence of the limited bandwidth, i.e. a time delay, in the measurement device, we should be aware that the input signal to the balance is composed of three signal components:

- 1) **Step input** which becomes effective in the very moment when the fluid stream is directed into the weighing tank. This input signal component is indicated in **Figure 8** as force  $F_0$ . The step signal causes high frequency harmonics that are damped by the measurement system as it can be seen in **Figure 8** (response curve 2).
- 2) **Ramp input** caused by the increasing liquid mass in the weighing tank. This signal component has low bandwidth requirements to be transmitted via the measurement device without signal distortion caused by delays.
- 3) **Quadratic time input** which originates from the decreasing impact force of falling liquid. Its bandwidth requirements are lower than with the ramp input signal due to the very low time derivative of this signal.

The résumé is that the approximation function 3 (**Fig. 8**) contains all the information to describe the dynamics of the filling process exactly from that time when the system's reaction to the step input has declined, so that approximation function  $F_{Approx}^*(t)$  can be used as a basis to determine the fluid flow rate  $\dot{m}_0$ :

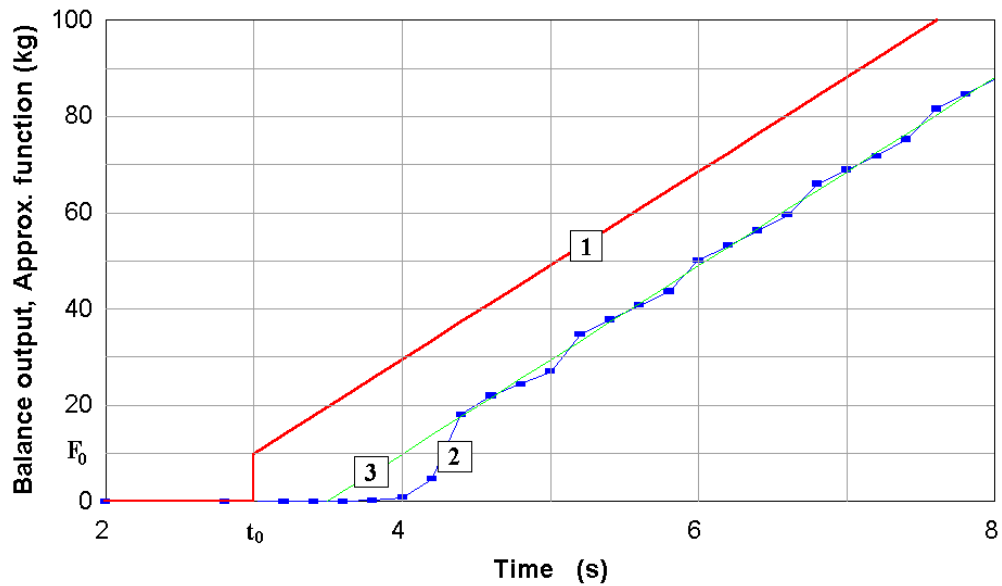
$$F_{Approx}(t) = a_0 + a_1t + a_2t^2 + \dots + a_nt^n \quad (11a)$$

$$F_{Approx}^*(t) = a_0 + a_1t + a_2t^2 \quad (11b)$$

### Measured Dynamic Response of the Weighing System

**Figures 8** through **10** depict the experimental results of the step response of an 1.5-tons balance, in case when the fluid flow is (suddenly) directed into the empty weighing tank (representing the input step to the system). As an example, the system response is diagrammed for 70 m<sup>3</sup>/h flow rate.

**Figures 9a** and **9b** show the system's transient response in comparison with different-type



**Figure 8.** Dynamic response of balance output signal:  
**1)** Time response of impact force, **2)** Measured system (electronic weighing system) response, **3)** Approximation function

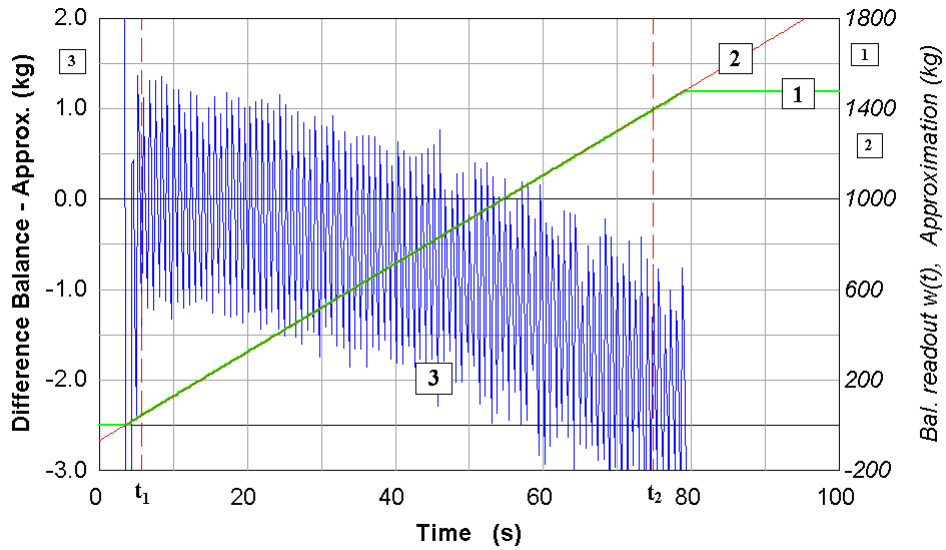
**Table 2.** Polynomial coefficients of different-type model approximation

Coefficient	Linear approximation	Quadratic approximation	Cubic approximation
<b>a<sub>0</sub> (kg)</b>	-68,425405311271	-68,425405311271	-68,421698294475
<b>a<sub>1</sub> (kg/s)</b>	19,567571022351	19,567571022351	19,567149243584
<b>a<sub>2</sub> (kg/s<sup>2</sup>)</b>	-	-0,000361658732	-0,000349384112
<b>a<sub>3</sub> (kg/s<sup>3</sup>)</b>	-	-	-1,0152052574E-07

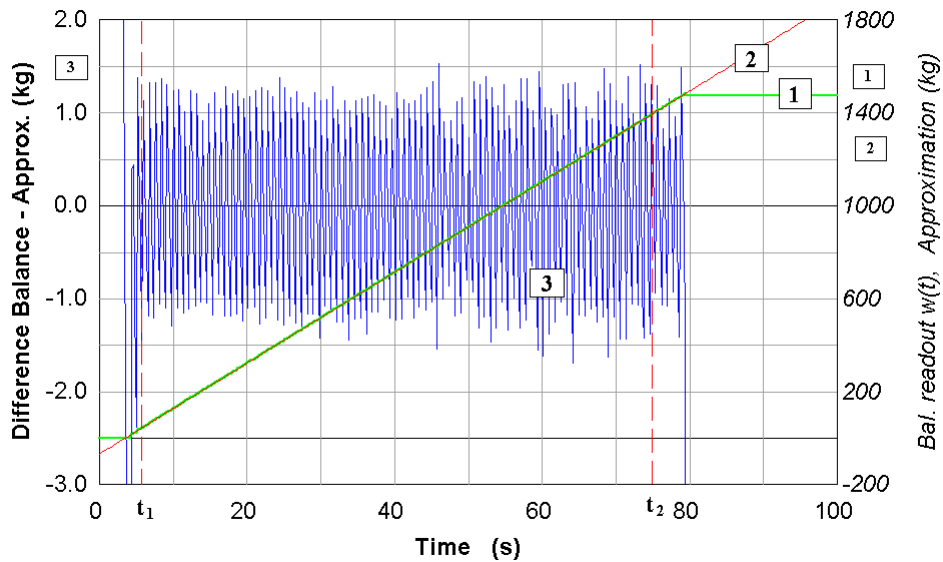
Parameter: Flow rate = 70 m<sup>3</sup>/h (345 sampled data points)

approximation functions (linear and quadratic approximations) whose parameters (i.e. polynomial coefficients) were determined by applying Least Squares Method (8) over 345 sampled data points.

The polynomial coefficients of different-order approximation functions for system reaction at 70 m<sup>3</sup>/h are displayed in **Table 2**. **Figure 9b** reveals that the quadratic function (curve 3) represents a good approximation of the transient response. The application of a cubic approximation function did not improve the results in this case.



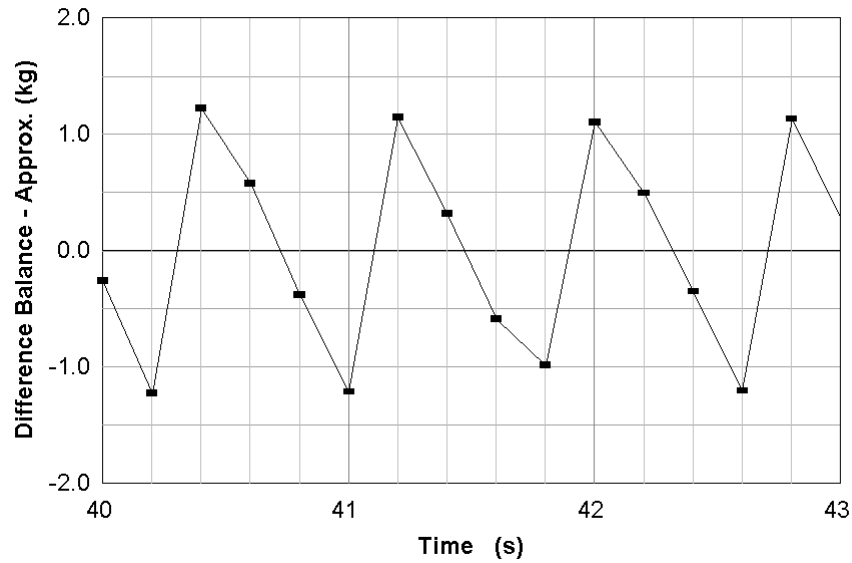
a)



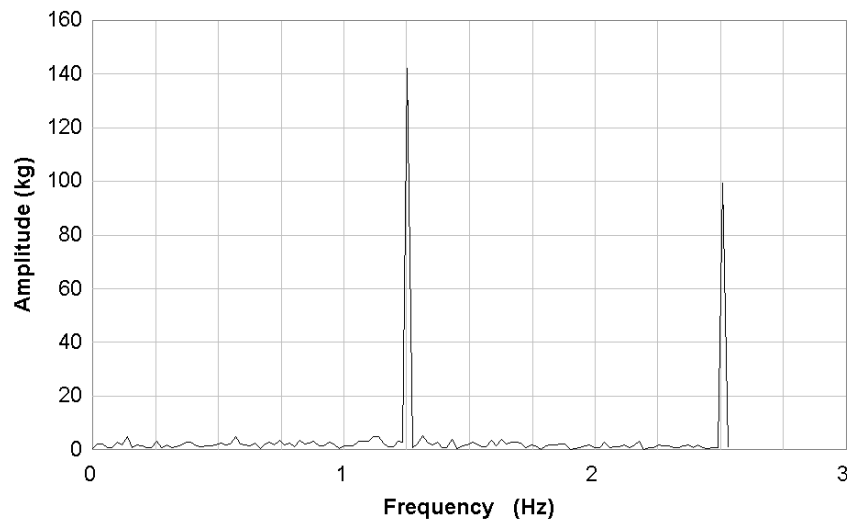
b)

**Figure 9.** Dynamic response of balance output signal  
*a) High-resolution zoomed view of the linear approximation model*  
*b) Same view of the quadratic approximation model*

To investigate what type of a signal (random or deterministic) we have in the difference signal of balance output signal minus approximation function, we have a closer look at curve 3 in **Figure 9b**, with a higher resolution of the time axis, which is to be seen in **Figure 10a**. And what we recognize is that there is a deterministic, periodic deviation of the balance signal from the quadratic approximation function. This signal deviation results from the tracking error of the control loop that is realized in the electrodynamic force-compensation load cell of the weighing system. A frequency analysis, shown in **Figure 10b**, illustrates that there are spectral peaks that result from the periodic signal tracking process of the load cells (a problem that would not occur if fast-response strain-gauge sensors were used with the weighing system); random contributions to the frequency spectrum (noise signal) being low in magnitude.



a)



b)

**Figure 10.** Analysis of balance output signal  
*a) High-resolution zoomed view of the quadratic approximation model (difference of balance output minus quadr. approximation)*  
*b) Frequency analysis by applying FFT to a)*

Finally it is important to mention that the measurands indicated through the balance readout, though being scaled in kilograms, are in reality forces of different origins (see **Equ. 6**) whose numerical magnitude equals to the formerly applied unit of force, the *kilopond*.

### ***How to Determine Mass Flow Rate from System Response Measured Data***

The measurement task we can realize now is to determine the magnitude of the constant input mass flow rate  $\dot{m}_0$  to the weighing system based upon the measurement data delivered from the balance signal output and applying the model-based approach. The procedure will be as follows:

- Least Squares Method is applied to measurement data coming from the balance in order to determine the polynomial coefficients of the approximation function **Equation 11b**.
- Coefficients  $a_1 = b_1$  and  $a_2 = b_2$  from **Equations 10** and **11b** are equated to determine mass flow rate  $\dot{m}_0$  from acquired process data (**Equ. 11b**) and from design parameters of the weighing system (**Fig. 6.** and **Equ. 9**).

The accuracy of this flow rate “measurement” depends on the time constancy of the flow rate and the exact knowledge of the size and magnitude of the system parameters. The degree of uncertainty of this knowledge determines the magnitude of the measurement uncertainty of the dynamic weighing process.

In order to determine the totalized flow or the mass passed through the meter under test, which is generally measured in a static weighing flow calibrator during the weighing tank’s filling, we have to calculate the time integral of the “constant” mass flow rate  $\dot{m}_0$  over the measurement time  $T_{Meas}$ .

## **Conclusions and Final Remarks**

Dynamic weighing methods are being utilized in liquid flow calibrators with great success for a long period of time due to the fact that they offer some essential benefits to the users. An obvious benefit is that they combine a gravimetric calibrator’s accuracy with relatively short time requirements for a meter’s calibration.

But in applying dynamic weighing we have to take into consideration the fact that any mechanical (and even electronic) device responds to an input action, or say input signal, with a delayed output action. This is due to the well-known fact that any system or device comprises energy storages, like mass, capacitors or inductors. Thus, generally spoken, the transfer function (i.e. the Laplace transform, describing the interrelation of the input and output signals) of a real system, or device like the weighing device in a flow calibrator reveals a frequency bandwidth limitation. This system behavior is to be considered when using an electronic balance for dynamic weighing.

In applying a model-based approach, the accuracy of dynamic weighing calibrators can be improved essentially and their system response behavior can be described on the basis of a mathematical model. This is necessary to make uncertainty investigation accessible to dynamic weighing calibrators.

The paper has shown that an electronic balance or force-measuring device, respectively, as a dynamic weighing system in a gravimetric flow calibrator may be considered to represent a mass flow-rate metering sensor with a high reproducibility and with the inherent properties of a “transfer” meter with an intermittent operation made. This "transfer" (force) meter can simply be calibrated with standard weights.

In order to utilize the benefits of dynamic weighing in liquid flow meter calibration and to perform further scientific investigation to improve its use in industry, with PTB’s new water test facility (6) special

provision was made to apply flying start and finish calibration both with static and dynamic weighing method.

## References

1. Shafer, M. J. and Ruegg, F. W. (1958), "Liquid-Flowmeter Calibration Techniques", *Transactions of the ASME*, October, pp. 1369-1375.
2. International Organization for Standardization (1980-12-15), "Measurement of liquid flow in closed conduits - Weighing method", *International Standard ISO*, Ref. No. ISO 4185-1980 (E).
3. Technical documentation of series 300 primary flowmeter calibration stands, *COX Instrument, Bensalem, PA, USA*.
4. Steuer, T. and Gams, O. (2001), "Investigations to determine delay time with lever balance dynamic calibrators", *Unpublished research report*, KEM Küppers Elektromechanik GmbH (Flowmeter manufacturer and calibration laboratory, accredited by DKD German Calibration Service), Karlsfeld, Germany.
5. Giesen, G. and Pfrang, J. (1999), "Untersuchungen zum Einsatz eines dynamischen Wägesystems als Durchfluß-Meßeinrichtung" (Investigation on the application of a dynamic weighing system as a flow metering device), *Unpublished research report*, Rota Yokogawa GmbH & Co. KG (Flowmeter manufacturer and calibration laboratory, accredited by DKD German Calibration Service), Wehr, Germany.
6. Pöschel, W. and Engel, R. (1998), "The Concept of a New Primary Standard for Liquid Flow Measurement at PTB Braunschweig", *Proceedings of the 9<sup>th</sup> International Conference on Flow Measurement, FLOMEKO '98*, 15.06. - 17.06.1998, Lund, Sweden
7. Richards, R.J (1993), "Solving Problems in Control", New York, NY, John Wiley & Sons, Inc.
8. Hamming, R.W. (1973), "Numerical Methods for Scientists and Engineers", 2<sup>nd</sup> Edition, New York, NY, McGraw-Hill.

## Acknowledgements

The author gratefully acknowledges T. Steuer and O. Gams of KEM Küppers Elektromechanik GmbH as well as G. Giesen and J. Pfrang of Rota Yokogawa GmbH for having performed essential investigations and measurements and made available their results to the author.