An incremental method to assess the linearity of gas flowmeters: application to Fleisch pneumotachographs

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An incremental method to assess the linearity of gas flowmeters: application to Fleisch pneumotachographs. C. Duvivier, R. Peslin, C. Gallina.
ABSTRACT: A new method of studying the linearity of gas flowmeters was tested on different models of Fleisch pneumotachographs. The method applies a steady flow to the test flowmeter, which is increased in a stepwise manner by adding a constant flow-increment. This is achieved using two flow sources in parallel. The method does not require any reference flow channel and may be implemented with standard laboratory equipment. Using this method, the gain of Fleisch pneumotachographs, whatever their size, decreased by about 2–3% from low flows to about 40% of their nominal full scale (FS), and then increased almost linearly with increasing flow. The error was 8–13% at 200% FS. The following equation was devised to correct the data at high flow: $\dot{V}c = \dot{V}t\,(1 - K\,(\dot{V}t - S))$ where $\dot{V}c$ and $\dot{V}t$ are the corrected and measured flow respectively, K a gain correction factor and S a flow threshold below which no correction is needed. Applying this correction with suitable coefficients, the maximal error was below 3% from 0–200% FS.
Eur Respir J., 1988, 1, 661–665.

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Gas flowmeters are extensively used in respiratory physiological studies, as well as in pulmonary function testing or monitoring. Most of them are based on a physical principle which should theoretically ensure a linear relationship between their output and the flow to be measured. An example is the pressure drop across a Fleisch pneumotachograph [1] which, ideally, is linearly related to flow by Poiseuille's law. In practice, however, a strict proportionality is not usually obtained for various reasons depending on the type of flowmeter. The degree of non-linearity is usually small over a limited range of flows, specified by the manufacturer, but may become quite substantial and be responsible for important errors when the device is used outside that range. An example is the use of a Fleisch no. 3 pneumotachograph in several commercialized systems to measure forced expiratory flows which, in healthy men, may be two or three times larger than the recommended full scale. In such instances a correction is obviously needed.

Accurate flow measurements therefore require that the linearity of the measuring device be precisely assessed. This is generally done either by using rotameters as a reference [2, 3], or by a volumetric method employing a large spirometer [4, 5, 6]. The first method has various limitations and is based on the assumption that the reference instrument is itself suitably linear. The second requires a cumbersome piece of equipment, not available in all laboratories. A third method has been recently proposed by YEH *et al.* [7]; it is

based on the analysis of the flow signal recorded during a large number of volume strokes given with a calibrated syringe. The latter method requires a computer and is probably not suitable for very large flows. Also, the data are probably influenced to some extent by the frequency response of the flow channel [4, 8]. The objective of this study was to evaluate an alternative method using commonly available equipment, which does not require a linear reference. The method is based on the summation of constant flow increments.

Principle

The method applies to the tested flowmeter (Ft) a steady flow ($\dot{V}_i$), which is increased in a stepwise manner by adding a constant flow-increment ($\Delta\dot{V}$). At any step i, $\dot{V}_i = i \cdot \Delta\dot{V}$. This is achieved by using two flow sources in parallel (fig. 1). The first (S_1) provides an accurately known flow equal to the selected flow increment. The second (S_2) is used to generate and maintain a steady flow equal to that achieved at the previous step ($\dot{V}_{i-1}$). Assuming that the flows delivered by S_1 and S_2 are not influenced by each other (high impedance sources), the procedure is as follows. At step 1, S_2 is shut and S_1 open; then $\dot{V}_1 = \Delta\dot{V}$. After reading the corresponding measured flow ($\dot{V}t_1$), as indicated by the tested flowmeter (Ft), S_1 is shut and S_2 is set to obtain the same reading ($\dot{V}t_1$) on Ft. At step 2, S_1 is

opened again so that $\dot{V}_2 = \dot{V}t_1 + \Delta\dot{V} = 2\cdot\Delta\dot{V}$. Then t_2 is read, S_1 is shut and S_2 adjusted again to have the same reading on Ft. This procedure is repeated until highest desired flow has been obtained. It increases flow ($\dot{V}$) by a fixed amount ($\Delta\dot{V}$) at each step and, therefore, provides a known input to the tested flowmeter over any range of flow.
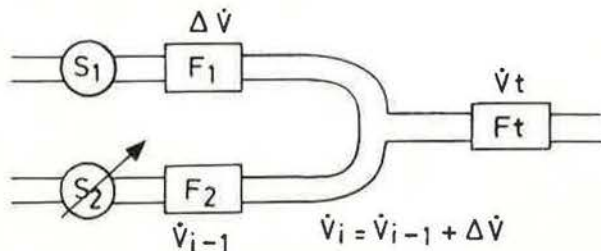

Fig. 1. – Principle of the method. The flow delivered to the tested flowmeter (Ft) at step i ($\dot{V}_i$) is the sum of the flow-increment ($\Delta\dot{V}$) generated by source S_1 (read and controlled by flowmeter F_1), and of the flow delivered at step i–1 generated by source S_2 (controlled by flowmeter F_2).

In practice, high flow sources have comparatively low internal impedances, so that the flow actually delivered may vary with the pressure upstream or downstream from them. When this is the case S_1 and S_2 will interfere with each other. For instance, the flow generated by S_2 will slightly decrease when S_1 is opened. It is, therefore, advisable to control the flow with flow-meters and, if necessary, adjust slightly the flows delivered by the two sources. The flowmeter (F_1) associated with S_1 must be precisely calibrated and should permit an accurate reading of $\Delta\dot{V}$, but needs not be linear as it is used to control a single flow value. The flowmeter (F_2) associated with S_2 must also be suitably precise, need not be linear, and does not even have to be calibrated. It is just used to detect and help correct any change in the flow delivered by S_2 when S_1 is opened.

To test its applicability, the method was used to study the linearity of various models of Fleisch pneumotachographs over flow ranges exceeding their nominal full scale.

Method

Two 800 W vacuum cleaners were used as flow sources. They were placed downstream from the tested flowmeter so that room air was drawn through it. As room temperature was kept at $20\pm2°C$, this ensured almost constant physical conditions of the gas in the flowmeter. The outputs of the two

sources could be precisely adjusted using variable-voltage autotransformers. A stopcock was placed upstream from S_1 to shut it completely when necessary. Each vacuum cleaner, which behaved as a low impedance source, was associated with a Fleisch pneumotachograph connected to a Validyne MP45 (±2 cmH$_2$O) differential pressure transducer. For F_1 a pneumotachograph type no. 1 was used for flow-increments of 0.1 and 0.2 $l\cdot s^{-1}$, and a type no. 2 for flow-increments of 0.4 and 1 $l\cdot s^{-1}$. For F_2, type 2 or 3 was selected according to the range of flows, so as to obtain a precise reading and remain within the operating range of the pressure transducer. The outputs of the two pressure channels were low-pass filtered (first order, $\tau=1s$) to minimize the noise, and read with digital voltmeters. The precision of the reading was usually better than 0.5%. F_1 was calibrated using rotameters. Due to pressure losses along the tubings, particularly at very high flows, the absolute pressure in F_1 (P_1) was slightly below that in the tested flowmeter (Pt). Therefore, volumic flows being inversely related to absolute pressures (Boyle's law), the flow-increment through Ft was slightly lower than through F_1. The difference between P_1 and Pt was measured at each step with a slanted water manometer, and $\Delta\dot{V}$ readings were corrected for that small error($\Delta\dot{V}$ corrected$=\Delta\dot{V}\cdot$Pt$/P_1$). The correction corresponded to only 0.2% of the reading at the nominal full scale of the pneumotachographs.

Tested pneumotachographs included Fleisch type nos 1–4. The pressure drop across them was measured with a Validyne MP 45 ($\pm$ 2 cmH$_2$O) differential transducer selected for its excellent linearity. The latter was studied using a high sensitivity slanted manometer as a reference. The gain of that transducer (voltage per unit pressure) was found to vary by less than 1% over its entire range of operation. The output of the pressure channel was low-pass filtered, as for F_1 and F_2, and read with a digital voltmeter. The pneumotachographs were always equipped on their upstream side with the metal cone screen (flow equalizer) and rubber cone provided by the manufacturer (Metabo Lausanne). These cones have been shown to influence the gain and linearity of the devices [4, 7]. The heating system was not used.

Non-linearity of flowmeters has been characterized in different ways in the literature [2, 7]. In this study we have used two characteristics: 1) the percentage difference between the largest and the smallest gains ($\Delta G\%$), i.e. between the largest and smallest value of $\dot{V}t/\dot{V}$ over a specified range of flows; a similar approach has been used by YEH et al. [7]; 2) the largest flow difference between any measured value and the "best straight line" fitted to the data (E, ml$\cdot s^{-1}$). The best line was defined as a line going through the origin ($\dot{V}t=0$, $\dot{V}=0$) with a slope such that the distance in question was minimal. The slope was found by a simple one-dimension parameter estimation routine.

Results and discussion

The variability of repeated measurements by a single observer and by several observers was assessed on a Fleisch no. 3 pneumotachograph. The results are presented in figure 2 in the method suggested by YEH *et al.* [7] which permits small differences to be visualized much more clearly than with the usual pressure-flow or flow-flow graphs: the gain of the transducer is plotted as a function of the flow input. Within and between-observer variabilities appeared to be below 0.5% of the measured gain from 0–100% of the nominal range of operation (FS) of the flowmeters. Larger and somewhat systematic differences, amounting to up to 2%, were seen when input flow was increased to 200% of that range. The differences were not larger between than within-observers. Thus the method allows the detection of subtle changes in the gain with very little noise and in a quite reproducible way: the gain of that pneumotachograph decreased by a few percent from low flows to about 40% of FS, and then increased with increasing flows.

A similar pattern was observed with all Fleisch pneumotachographs investigated, whatever their size, the gain curves being very similar when flow was expressed as a percentage of FS (fig. 3). The particular behaviour observed at low flows agrees with data provided by the manufacturer and has previously been reported by YEH *et al.* [7]. The two indices characterizing the degree of non-linearity for two ranges of flow (100% FS and 200% FS) are presented in table 1. It can be seen that the maximal change in gain (ΔG) does not exceed 3.3% from the lowest measured flow (10–15% FS) up to 100% FS. On the same range, the maximal distance to the "best line" (E) increases in proportion to the size of the pneumotachograph when expressed as absolute flow, but is similar with all devices and below 1% when related to FS flow (E/FS ranging from
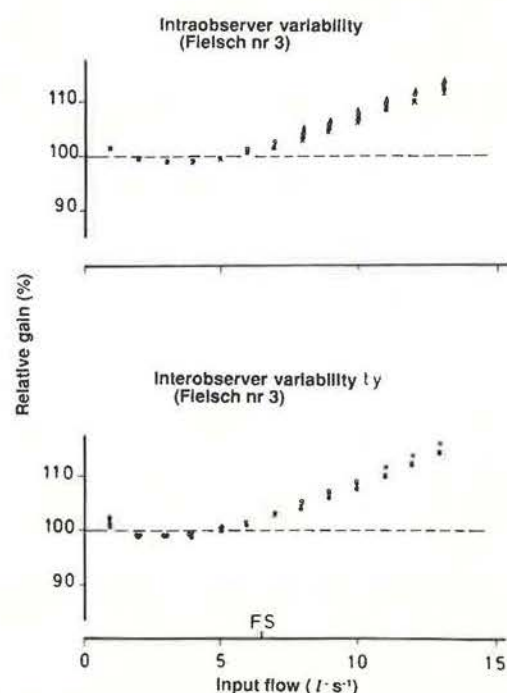

Fig. 2. – Relative gain of a Fleisch no. 3 pneumotachograph as a function of flow. Top: data from four runs by the same observer; bottom: data from three different observers. The 100% of the gain scale is arbitrary and corresponds to the average gain observed between 0 and 50% of the nominal range of the pneumotachograph, as defined by the manufacturer (FS). Measurements were made up to 200% of the upper limit of that range.

0.004 to 0.007). Non-linearity is, of course, much more pronounced when the range is extended to 200% FS with ΔG of up to 13%. The table also shows that almost identical data were obtained with three different pneumotachographs of the same type.

For accurate measurements over an extended flow range, it is clearly necessary to correct the signal

Table 1. – Indices characterizing the non-linearity of Fleisch pneumotachographs and correction coefficients

Type no.	Upper end of flow range $l \cdot s^{-1}$	Uncorrected ΔG %	Uncorrected E $ml \cdot s^{-1}$	Correction coeff. K $l^{-1} \cdot s$	Correction coeff. S $l \cdot s^{-1}$	After correction ΔG %	After correction E $ml \cdot s^{-1}$
1	1.0	0.7	4				
1	2.0	10.0	51	0.061	0.68	0.5	6
2	2.5	1.7	17				
2	5.2	10.8	149	0.026	1.84	0.6	19
3	6.5	1.6	42				
3	13.0	13.0	486	0.011	4.44	1.5	109
3'	13.0	13.4	490	0.011	4.30	1.3	115
3"	13.0	13.3	493	0.011	4.24	1.1	137
4	11.0	3.3	68				
4	22.0	7.7	684	0.006	11.1	2.8	220

Types 3, 3', 3" correspond to different pneumotachographs of the same type. Upper end of flow range is either the nominal value specified by the manufacturer, or 200% of that value. ΔG: maximum change in gain; E: maximal distance to best line, as defined in the text; K and S: coefficients of correction from equation given in text.

recorded from a Fleisch pneumotachograph. This may be easily achieved when the signal is processed with a digital computer, as is now frequently the case. It has been shown by YEH *et al.* [7] that a quadratic fitting of the pressure-flow characteristics does not provide an accurate correction. Indeed, it would only be adequate if the gain increased linearly with flow, which is only the case above 50 or 60% FS. On the basis of this observation, one
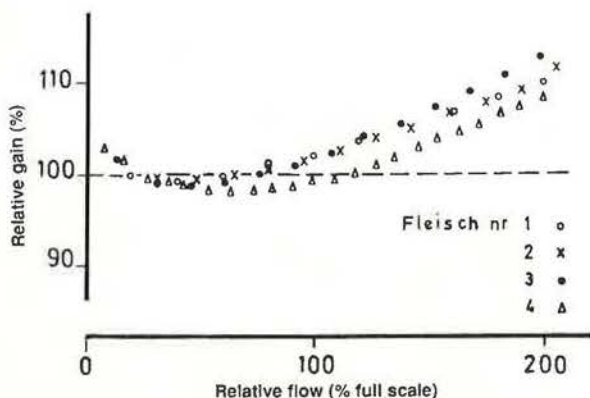

Fig. 3. – Relative gain of Fleisch pneumotachographs nos 1–4 as a function of flow expressed as a percentage of the nominal range. Gain scale as in figure 2.
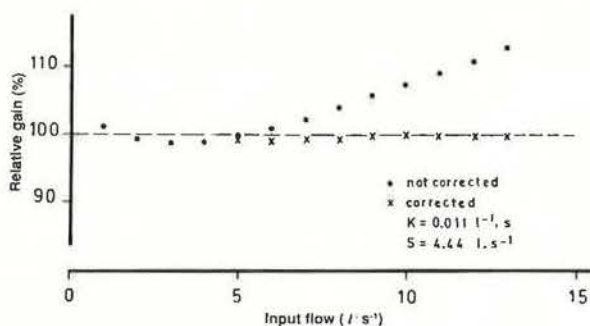

Fig. 4. – Relative gain of a Fleisch no. 3 pneumotachograph as a function of input flow, from uncorrected data and from data corrected with the equation given in the text.

could expect a better correction to be obtained using the following relationship where Vc and Vt (in $l \cdot s^{-1}$) are the corrected and measured flow, respectively:

$$\text{For } \dot{V}t < S \quad \dot{V}c = \dot{V}t$$
$$\text{For } \dot{V}t > S \quad \dot{V}c = \dot{V}t(1 - K(\dot{V}t - S))$$

In this equation S ($l \cdot s^{-1}$) is a flow threshold below whic no correction is applied, and K ($l^{-1} \cdot s$) a gain factor applied to the difference between the measured flow and the flow threshold. It should be noted that the equation does not correct for the initial

decrease in gain from low flows to 40% FS. Values of K and S have been obtained from the data using a two-dimension parameter estimation algorithm (alternating variable method [9]) and are shown in table 1. The values of ΔG and E for the corrected flow signal are also presented. Corrected and uncorrected gains for a Fleisch no. 3 pneumotachograph are shown on figure 4. It may be seen that the correction considerably reduces the degree of nonlinearity. The residual ΔG is invariably due to the larger gain at low flows, which is not corrected for by the equation. The residual E does not correspond to any systematic behaviour and rather represents random noise in the measurements. K and S values given in table 1 are not unique, and a number of combinations of the two coefficients would provide as good a correction.

The above data suggest that the investigated method is a practical and valuable means for studying the linearity of gas flowmeters. It certainly requires careful measurements, as do all calibration procedures, but was found to be fairly easy to use with a little practice. In this study it was implemented using relatively expensive equipment to control the flows from the two sources. However, it may be applied using much simpler equipment such as water manometers. Besides the fact that it does not require any linear reference instrument, a useful feature of the method is that it permits work on virtually any flow range, which is not the case with commonly available rotameters or spirometers.

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RÉSUME : Une nouvelle méthode d'étude de la linéarité des débitmètres gazeux a été testée sur différents modèles de pneumotachographes de Fleisch. La méthode consiste à appliquer au débitmètre testé un courant continu, qui est augmenté par étapes en y ajoutant un échelon de débit constant. L'on arrive à ce résultat en utilisant deux sources de débit mises en parallèle. La méthode ne nécessite aucun debitmètre de référence et peut être réalisée avec un équipement standard de laboratoire. Cette méthode a permis de déterminer que le gain des pneumotachographes de Fleisch, quelle que soit leur taille, diminuait d'environ 2 à 3% depuis les bas débits, jusqu'à 40% de leur pleine échelle nominale, et augmentait ensuite de façon quasi linéaire avec l'augmentation du débit. L'erreur est de l'ordre de 8 à 13% à 200% de la pleine échelle. L'équation suivante a été élaborée pour corriger les données à haut débit: $\dot{V}c = \dot{V}t\,(1-K\,(\dot{V}t-S))$ où $\dot{V}c$ et $\dot{V}t$ sont respectivement le débit corrigé et le débit mesuré. K est un facteur de correction, et S le seuil de débit en dessous duquel aucune correction n'est nécessaire. Si l'on applique cette correction avec les coefficients adaptés, l'erreur maximale restait inférieure à 3% entre 0 et 200% de la pleine échelle nominale.