

ELECTROSTATIC NONINTRUSIVE METHOD FOR MEASURING THE FLOW RATE OF INSULATING FLUIDS

ISSN -1817 -2695

FAWZI M. MUSTAFA

*Department of Electrical Engineering, College of Engineering,
University of Basrah*

((Received 12/4/2011, Accepted 19/6/2011))

ABSTRACT

Theoretical analysis is given here showing the existence of a linear relationship between the mean velocity in a pipe \bar{v} and the mean frequency $\bar{\omega}$ in the spectrum of the noise signal caused by the passage of electrostatic charges carried by the flow as picked up by a suitable system of electrodes.

The analogue electronic circuit required to obtain $\bar{\omega}$ is built and tested in a flow circuit employing air. The experimental results confirmed the linear relationship expected theoretically and the error in the reading is about $\pm 2\%$.

Key words- Electrostatic method, electric charge, flow rate measurement.

1. INTRODUCTION

There are many different varieties of nonintrusive measurement methods based on the phenomenon of electrostatic induction. The method has been specially developed to measure the electric charge carried on solid particles in the pipes of pneumatic transport or in air, as well as to indirectly evaluate, determine, or estimate the following mechanical parameters of the two-phase gas-solid flows: mass flow rate, concentration, volume loading, and velocity. Incidentally, only one variety of method exists, which has been extensively developed, modified, described mathematically, and applied to practical laboratory and industrial installations. It is one in which a full-ring-shaped metal electrode (probe, sensor, etc.) is used on which electric charge is induced when exposed to the electric field of a single charged particle or flux of charged particles as, e.g., in a pipe of pneumatic transport. The charged particle or charged particles aligned can travel rectilinearly along the ring's geometrical axis or any other axis parallel to that geometrical one [1]-[12].

Some of the electrode designs are not full-ring shaped and can be one of the following: split-ring probes [13], quarter-ring probes [14], half-ring probes [19], and pin electrodes [3].

There are some papers which reviewed some achievements in developing the electrostatic measurement method [3], [6], [16]-[18]. They describe the methods and their varieties only in the context of other nonintrusive methods for the measurement of the mass flow rate, velocity, etc., such as capacitance, ultrasonic, microwave, optical, conductivity, thermal, etc., methods. A lot of works have been published, but most of them are very similar to each other, and the differences are only in some small modifications in the measuring electrode (probe) itself or in the head in which the probe is placed. There are also different theoretical approaches to mathematical modeling, as well as to developing the method and its application to many industrial situations.

There are many real devices, such as noncontact, nonobstructive probes, sensors, or transducers that are intended to work as a part of measuring instruments or system and to sense

changes in the flow of charged particles, mass flow rate, concentration, velocity, space-charge density, etc. [3], [5], [16], [19]-[23]. These detectors have been designed according to the method and they operate on the basis of electrostatic induction when exposed to an electric field of those particles. They were modeled mathematically and have been described in numerous papers.

Electrostatic nonintrusive system for measuring the velocity of charged particles in pipe flow is usually composed of sensing means in the form of one or multiples electrodes connected together in a certain manner and placed in proximity to the flowing fluid, Fig.1. Electronic circuits are used to detect and analyze the electric potential induced between the electrodes which is a result of the passage of electrostatic charges generated and carried by the flow past the electrode's region [24]. Such devices are intended for use in insulating fluids such as oil, gases and two-phase gas-solid flow.

A linear relationship between the mean fluid velocity \bar{v} in a pipe flow and the mean frequency $\bar{\omega}$ in the spectrum of the noise signal caused by the passage of electrostatic charges carried by the flow has been established in [19] and [20] where $\bar{\omega}$ is defined by the relationship

$$\bar{\omega} = \frac{\int_0^{\infty} \omega W(\omega) \cdot d\omega}{\int_0^{\infty} W(\omega) \cdot d\omega} \quad (1)$$

where $W(\omega)$ is the power spectrum density of the flow-signal. An analogue electronic circuit has been built and tested to obtain the mean frequency $\bar{\omega}$ from eqn.(1). The circuit required two analogue multipliers, dc divider and a special filter whose output should be proportional to $\sqrt{\omega}$ in the input signal. This last circuit requires a complicated process of design and implementation [21].

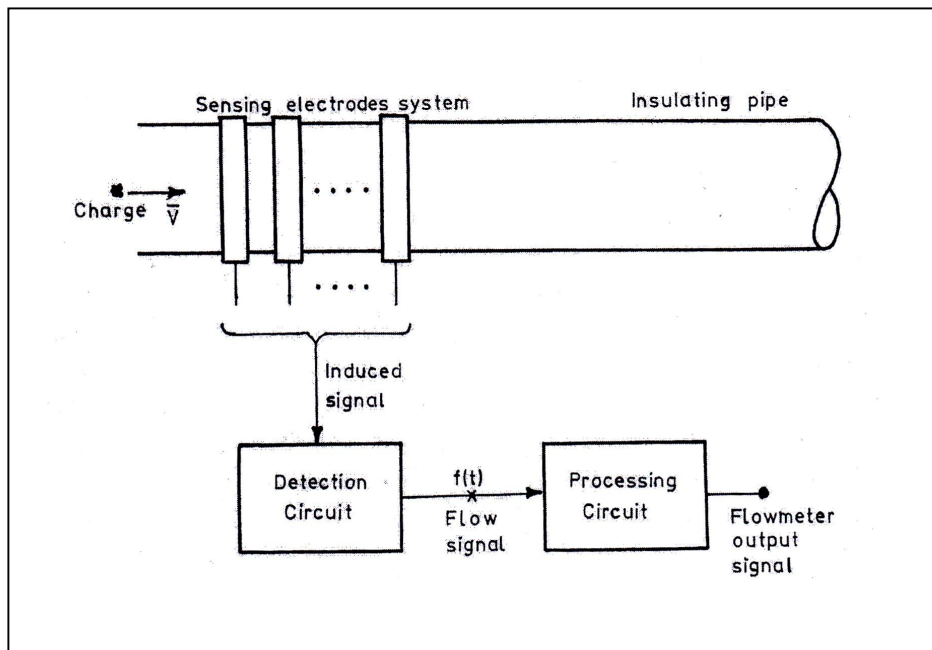


Fig.1 Electrostatic non-contact measurement system

In this paper, a new method for processing the induced signal is presented using a new formula, giving below, which proved to be much easier to realize in practice

$$\bar{\omega} = \frac{\int_0^{\infty} |f'(t)| \cdot dt}{\int_0^{\infty} |f(t)| \cdot dt} \quad (2)$$

where f and f' are the flow signal and its time derivative respectively.

2. THEORY

In the case of a steady highly turbulent flow, the velocity profile is independent of the flow rate, and the spatial distribution of the electrostatic charges in the flow is independent of the mean velocity of the fluid \bar{v} , and the distribution of charged particles along a stream line in the flowmeter is independent of \bar{v} . However, the magnitude of the charge may be dependent on \bar{v} [19].

Therefore the charge density $\rho(t, \bar{v})$ at a fixed point inside the pipe and hence the induced signal $f(t, \bar{v})$ at the electrodes may be taken as a random function of the position ($\bar{v} t$) and the fluid mean velocity \bar{v} and may be written as,

$$f(t, \bar{v}) = A(\bar{v})h(\bar{v}t) \quad (3)$$

where A is a constant amplitude depending on \bar{v} and h is a random function different at various points. Differentiating Eqn.(3) gives

$$f'(t, \bar{v}) = \frac{d}{dt} [A(\bar{v})h(\bar{v}t)] \\ = \bar{v}A(\bar{v})h'(\bar{v}t) = \bar{v}A(\bar{v})H(\bar{v}t) \quad (4)$$

where $H(\bar{v}t) = h'(\bar{v}t)$

The process in Eqn.(4) is equivalent to multiply $f(t, \bar{v})$ by the frequency ω in the frequency domain. Therefore the relation given in Eqn.(2) earlier becomes a form of mean frequency in the power spectrum of $f(t, \bar{v})$. Substituting f and f' into Eqn.(2) gives

$$\bar{\omega} = \frac{\int_0^{\infty} |\bar{v} A(\bar{v}) H(\bar{v}t)|.dt}{\int_0^{\infty} |A(\bar{v}) h(\bar{v}t)|.dt}, \text{ from which}$$

$$\bar{\omega} = \bar{v} \frac{\int_0^{\infty} |H(\bar{v}t)|.dt}{\int_0^{\infty} |h(\bar{v}t)|.dt}$$

$A(\bar{v})$ may be eliminated since it is not a function of time. Putting $\bar{v}t = \tau$ as a new dummy variable, the last equation becomes

$$\bar{\omega} = \bar{v} \frac{\int_0^{\infty} |H(\tau)|.d\tau}{\int_0^{\infty} |h(\tau)|.d\tau} = \bar{v}K \quad (5)$$

where K is independent of \bar{v} and is constant for a fixed fluid, flowmeter geometry and velocity profile. It is seen therefore that under the assumptions given the mean frequency is linearly dependent on the mean fluid velocity. Thus giving a basis for a new linear fluid flowmeter.

3. MEASUREMENT SETUP

3.1 FLOW HEAD AND FLOW CIRCUIT

A full-ring-shaped electrostatic flow probe has a linear static characteristics [25]- [28]. Therefore a number of such copper ring probes are chosen as sensing electrodes mounted on the outer diameter of a plastic ABS pipe, see Fig.2. These rings are forming two groups of

electrodes connected alternately and separated by gaps which are also wrapped with similar copper strips. The whole assembly is covered round with a ground earth shield to reduce external interferences.

The flow head is inserted in a flow circuit in which a blower is used to draw atmospheric air and blow it across the flowmeter, The flow mean velocity is measured using a pitostatic

tube and the air flow velocity is adjusted using a flap placed at the entrance of the blower, see Fig.3.

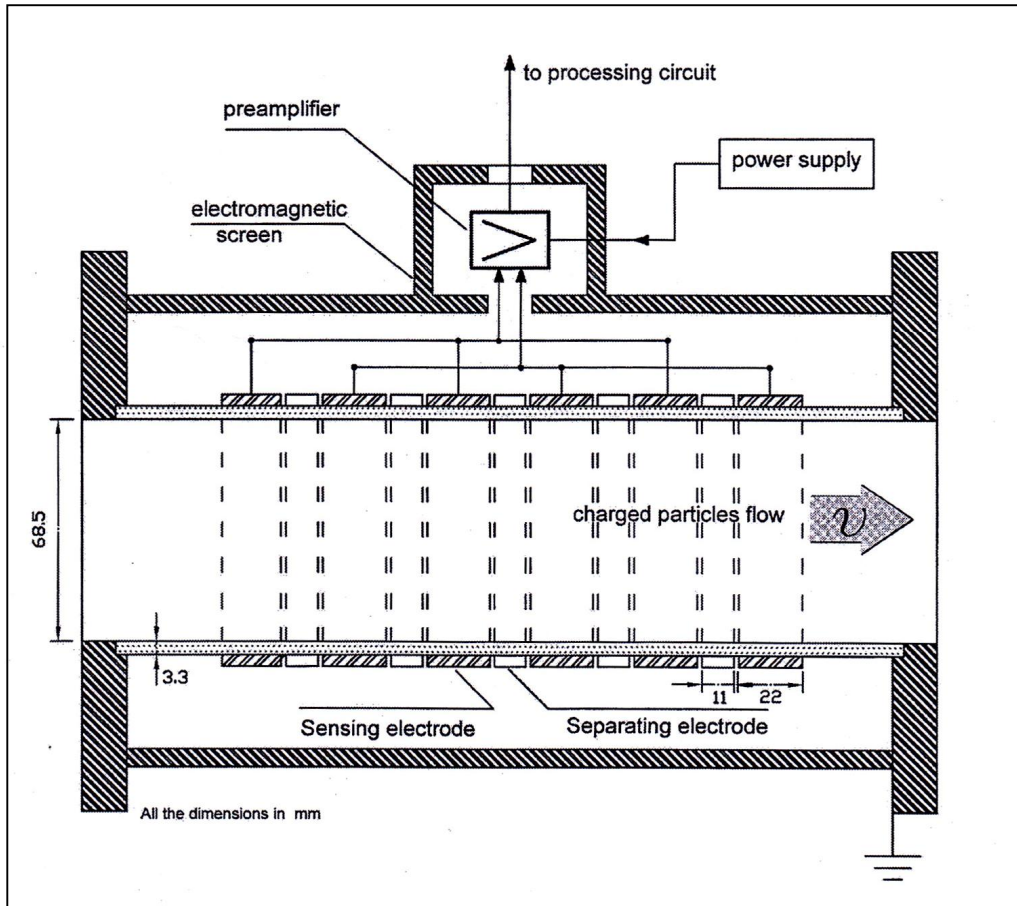


Fig.2 Detail of the flow head

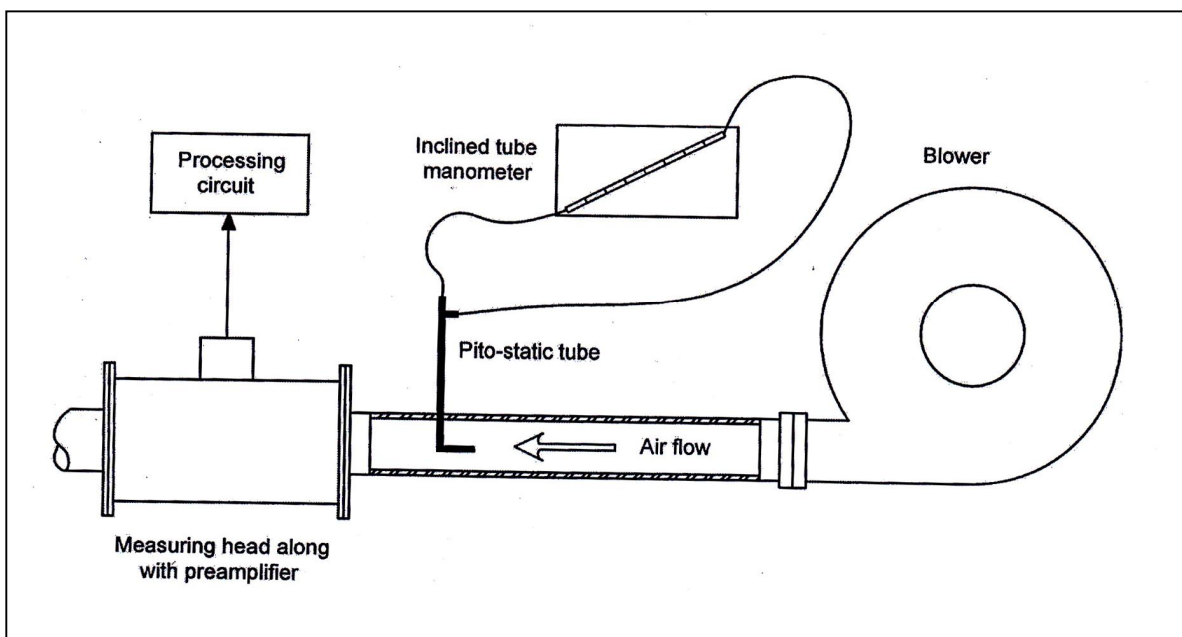


Fig.3 Experimental setup of measurement system

3.2 PREAMPLIFIER CIRCUIT

As the flow signal is picked up capacitively, the output impedance of the flow head becomes extremely high. Therefore the detection preamplifier stage should have a matching high input impedance. Otherwise most of the signal is lost and the noise level increases to become dominant.

A pair of high input impedance operational amplifier with JFET input has been used in a

differential configuration. This reduces the common mode interfering signal to a very large degree. The circuit diagram is given in Fig.4. The circuit is composed of two unity gain similar high input impedance buffer amplifiers followed by a differential amplifier of unity gain, followed by an amplification stage in order to adjust the flow signal to an acceptable level.

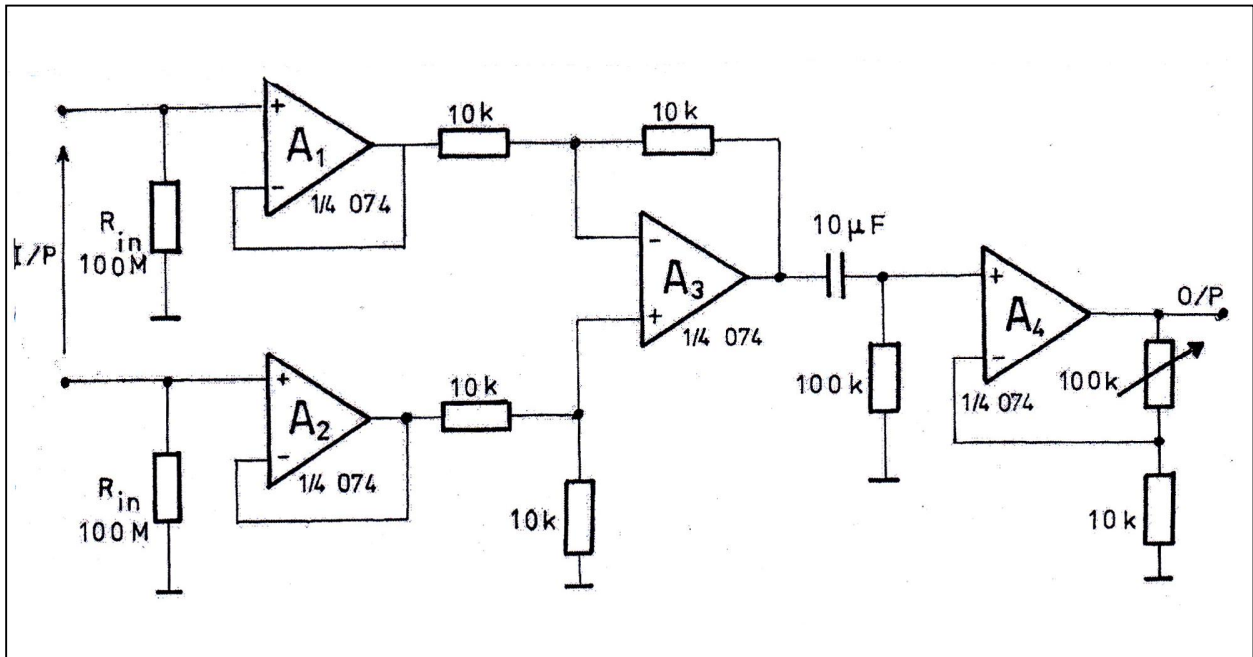


Fig.4 Circuit diagram of the detection preamplifier

3.3 PROCESSING CIRCUIT

The processing circuit for a practical flowmeter should be simple not requiring expensive components. Eqn.(2) suggests a simple method for obtaining the mean frequency in the flow signal. Referring to Fig.5, the upper branch is composed of a differentiator followed by an absolute value circuit and a simple low pass filter. This branch gives the numerator of Eqn.(2). The lower branch is composed of an

absolute value circuit and a low pass filter similar to those in upper branch and gives the denominator of Eqn.(2).

A divider is then used to divide the d.c. voltages obtained from the upper and lower branches to give the flowmeter output signal.

This circuit has been built and calibrated using a sinusoidal signal of varying frequencies. The calibration results are given in Fig.6.

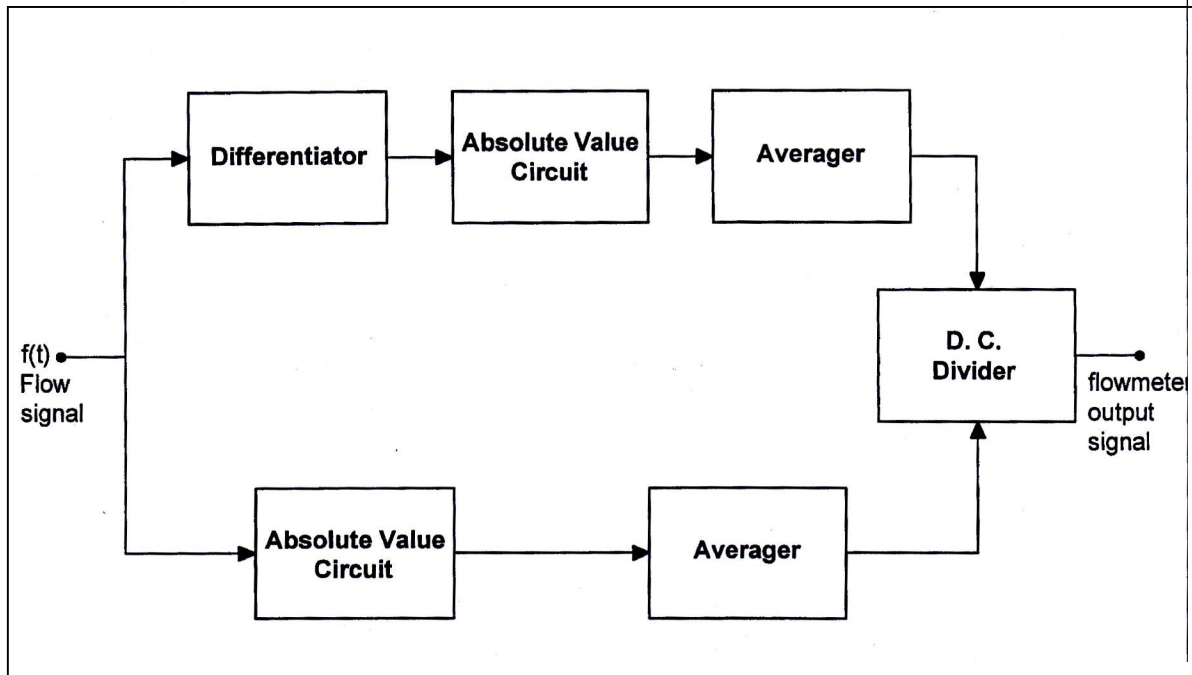


Fig.5 Block diagram for processing the flow induced signal

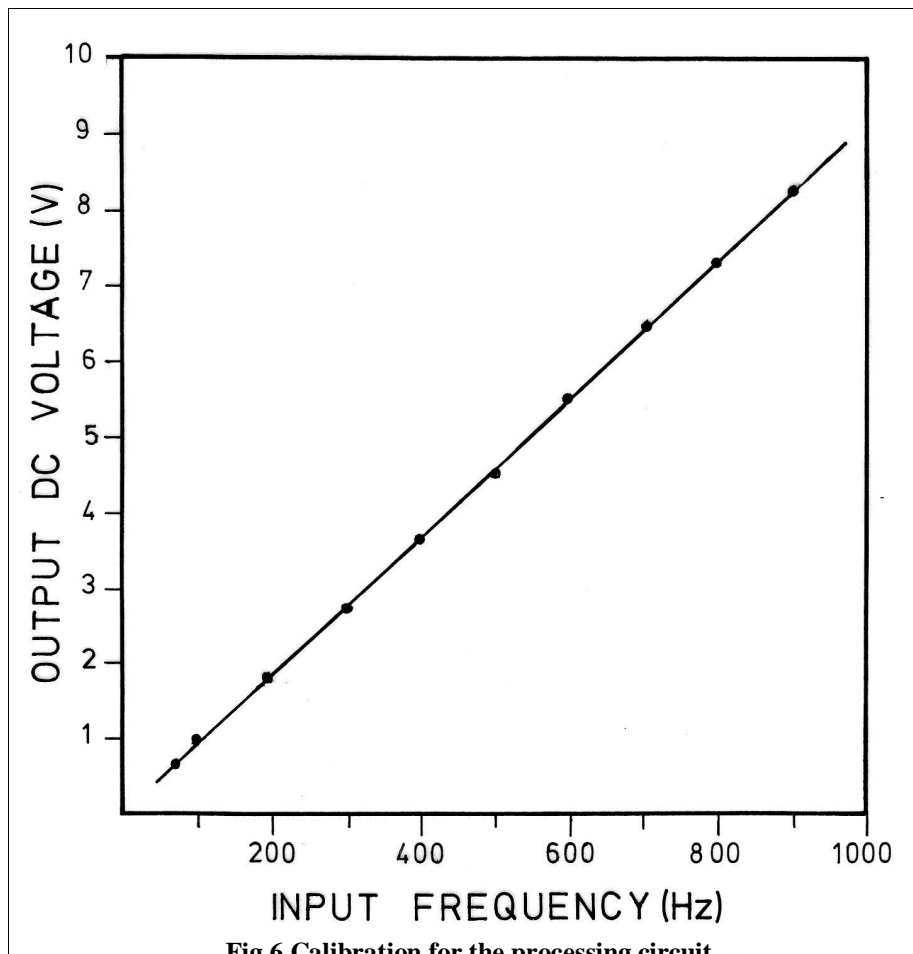


Fig.6 Calibration for the processing circuit

4. EXPERIMENTAL RESULTS

The detection preamplifier circuit was fitted to the flow head and the induced flow signal on the electrodes was observed on the oscilloscope. Two samples of this noise like signal is shown in Fig.7 and 8 for different mean velocity values. The figures show clearly the decrease in high frequency components as the fluid velocity is reduced. The analyzing circuit was then introduced and its d.c. output was recorded for different mean velocity readings. These tests

were carried out for two cases. In the first, the separating electrodes were grounded and in the second these electrodes were left floating. See Fig.9 and 10. The graphs indicate a clear linear relation between the mean frequency, represented by the output of the processing circuit, and the mean fluid velocity as expected in the theoretical treatment in section 2. The error in the flowmeter reading is estimated to be $\pm 2\%$.

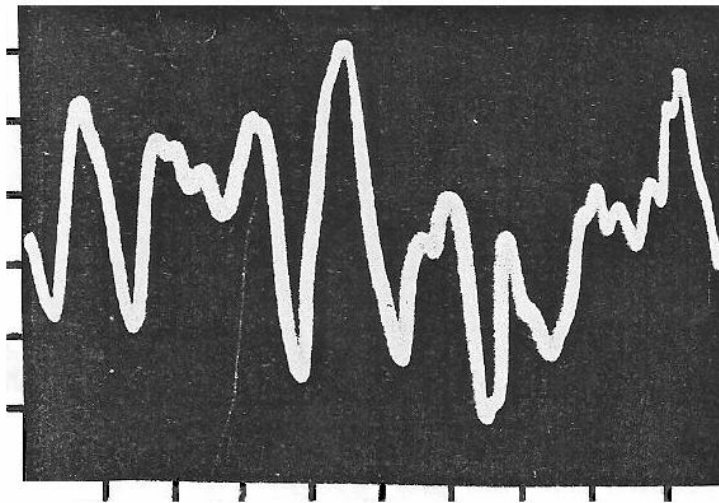


Fig.7 Voltage induced at the electrodes ($\bar{v} = 15$ m/s)
($V/D= 2V$, $T/D= 5$ ms)

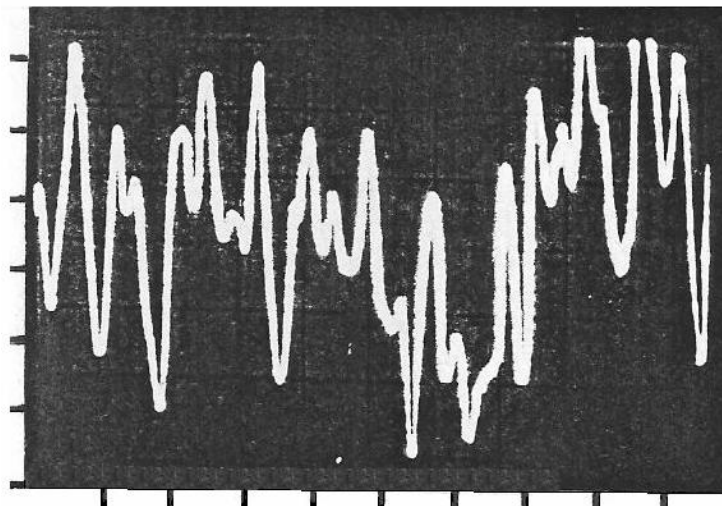


Fig.8 Voltage induced at the electrodes ($\bar{v} = 40$ m/s)
($V/D= 2V$, $T/D= 5$ ms)

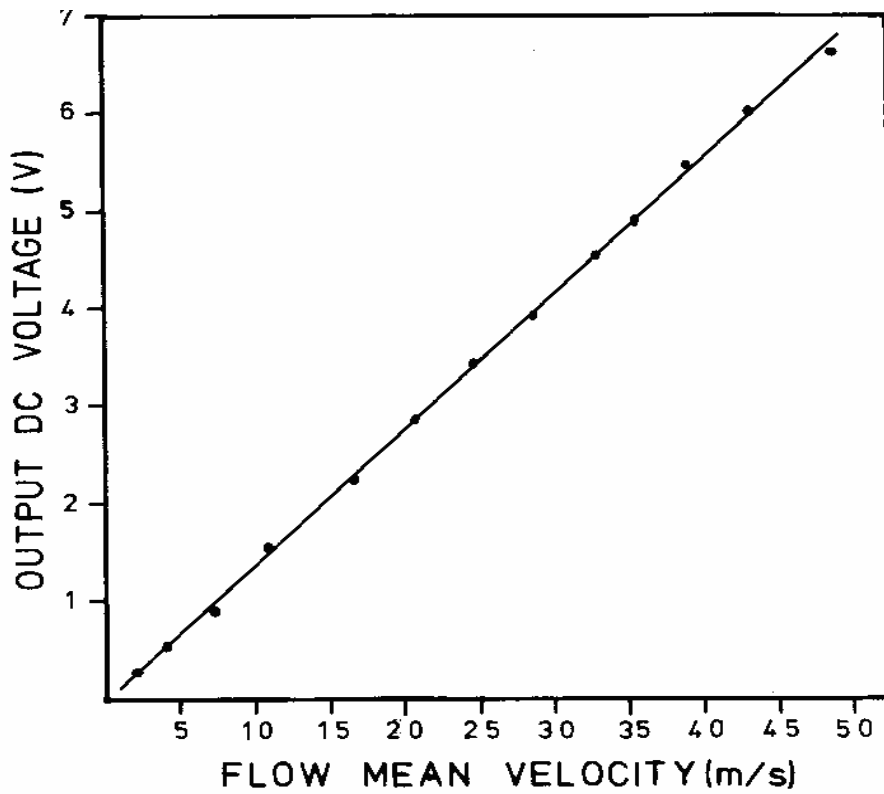


Fig.9 Flowmeter output vs. flow mean velocity
(separating electrodes grounded)

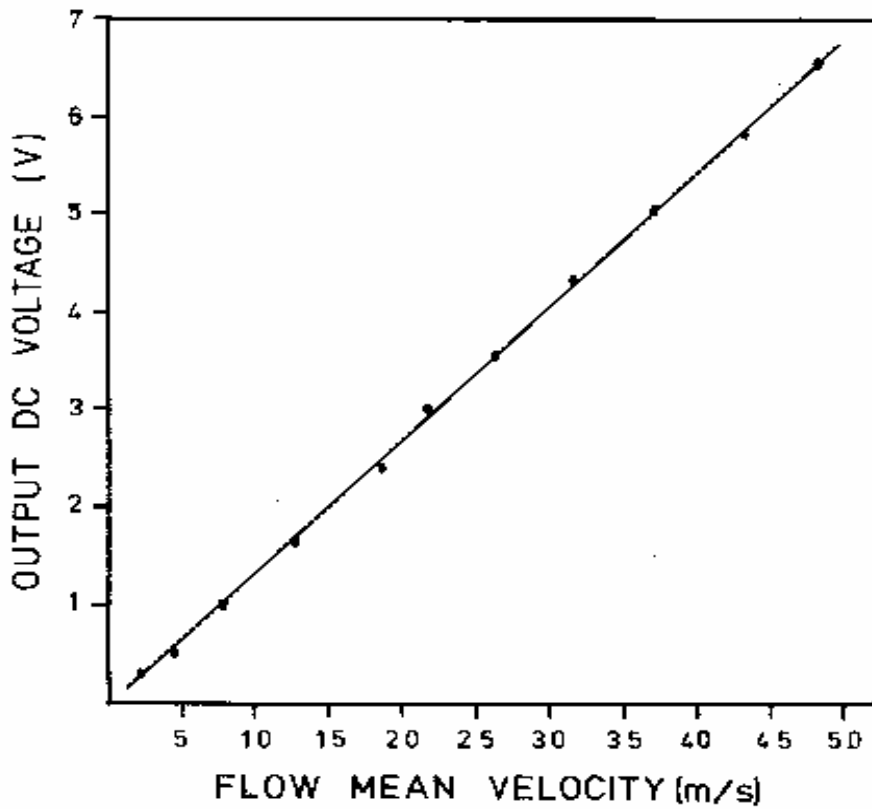


Fig.10 Flowmeter output vs. flow mean velocity
(separating electrodes floating)

5. CONCLUSION

A new method for measuring the flow rate of insulating liquids and gases has been described. The analysis showed an inherent linear relationship between the output and the input of the device and the experiments carried out support this analysis. The processing circuit is simple requiring few simple and common electronic elements. The resultant flowmeter is bidirectional, accurate, does not obstruct the flow and requires no energy to run other than that necessary for operating the electronics.

The numerical value of the calibration factor of the flow meter cannot be predicted theoretically using the present analysis. It is recommended, therefore, that a detailed solution of governing equations is carried out in a future work in order to be able to calibrate this electrostatic flowmeter.

It is also recommended that a future work may consider the merits of different electrode configuration as related to the flowmeter sensitivity to the changes in the flow profile for the same flow rate values.

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الملخص

تتاول هذا البحث الكشف عن العلاقة النظرية الخطية الموجودة بين معدل سرعة جريان الموائع v ومعدل التردد ω المحسوب من تحليل اشارة الضوضاء الناتجة من مرور الشحنات الكهروستاتيكية المتولدة والمحمولة مع الموائع اذا ما وجدت الالكترودات المناسبة لتحسس (او النقاط) هذه الاشارة .

الدائرة الالكترونية المطلوبة لالتقاط الإشارة وتحليلها وحساب ω قد بنيت واختبرت بنظام جريان مستخدماً الهواء الجوي . النتائج العملية الناتجة اكدت العلاقة الخطية المتوقعة نظريا" بنسبة خطأ تتجاوز 2%.