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1981 J. Phys. E: Sci. Instrum. 14 981

(http://iopscience.iop.org/0022-3735/14/8/021)

J. Phys. E: Sci. Instrum., Vol. 14, 1981. Printed in Great Britain

A new method for processing the signals from a laser dual-focus velocimeter

Yao Loh and Hung Tan†
The Institute of Mechanics, Academia Sinica, Peking, China

Received 26 August 1980, in final form 26 January 1981

Abstract A new method for processing the signals of a laser dual-focus velocimeter is proposed. The key idea is the simultaneous use of two independent electronic systems, each taking one focus as its detector for start pulses. One of the two systems always secures the 'incorrect' stop pulse, while the other can receive 'correct' and 'incorrect' stop pulses. The real flight time can be obtained by comparing the data from the two systems. The relation between the counts and the probability of a particle travelling directly from the first focal point to the second is analysed by statistical theory. A simple practical method of measurement has been established and proved to be reliable for a transonic free air jet experiment.

1 Introduction

Development of the laser dual-focus velocimeter (L2F) was first reported in 1975 by Schodl and Lading (Schodl 1975, Lading 1975). The basic idea is to measure the time of flight of particles by concentrating the laser energy upon two spatially separated foci. Because of the extremely high light intensity contrast between bright and dark regions in the measuring volume, such a system has a high signal-to-noise ratio. The distance between the two foci is 300–600 μm, which is far greater than the distance between interference fringes, the latter being of order 1 μm. Thus the frequency response of an L2F signal processor can be 2–3 orders lower than that of LDV systems. This advantage is especially important for high velocity measurement and makes the L2F method very effective for such applications. Unfortunately, most particles do not travel directly from one focus to the other. According to our experimental results obtained by using the present method, the probability of a particle successively crossing the two foci is about 0.1–0.3 for a free air jet.

When a particle passes through the first focal point it generates a start pulse. We define the stop pulse generated by the same particle that has travelled from the first focus to the second as the 'correct pulse'. Digital correlation technique and multichannel analysis are both practical methods to measure the mean flight time between the start and the 'correct pulse'. But in theory and practice, these two methods cannot answer the question of how to distinguish the real fluctuation of the flight time and time interval fluctuation caused by an 'incorrect' stop pulse. This has been a major shortcoming in the development and application of the L2F velocimeter.

Here we propose a new principle by which the above problem can be solved. The key idea is to use simultaneously two independent electronic systems, identical in structure but operated in reverse order, each of which takes a different one of dual foci as its own detector in registering a start pulse. One, called system 1, takes the upstream focus to initiate a start pulse as soon as an entering particle is detected and uses the downstream focus to issue a stop signal upon detecting the first arrival of a particle during a given time period T after the start pulse. The other system, called system 2, operates in the same manner except with the two foci reversed in order, that is, using the downstream focus for start and the upstream one for stop signals. Thus system 1 cannot distinguish between a 'correct' and an 'incorrect' stop signal. On the other hand, system 2 can receive, in principle, only the 'incorrect' stop signals if the dual foci are well aligned with the local mean stream direction; this condition can be achieved by varying the position of the downstream focus and the time period T until the ratio of the stop events from the two systems reaches a peak. The time between a start and its 'correct' stop signal and the probability of registering the 'correct' one are given by comparing the data given by the two systems. The relation between the counts and the probability is analysed by statistical theory. A simple practical method of making such measurements has been established and proved to be reliable for transonic free air jet experiment. It is also possible to use this method for studying the diffusion and structure of turbulence.

2 Structure and principle

The experimental set-up of the L2F velocimeter is shown in figure 1. An Ar$^+$ laser (2 W) serves as the light source. Using a Wallaston prism as a splitter, two parallel focused beams A and B are formed in the measuring volume (Loh *et al* 1980). This set-up is basically the same as that used by Schodl (1975) or Lading (1975).

The structure of the electronic systems is shown schematically in figure 2. Systems 1 and 2 are symmetric. The only difference between them is that the focus A is the start pulse source of system 1 and at the same time is the stop pulse of system 2. The logic process is as follows:

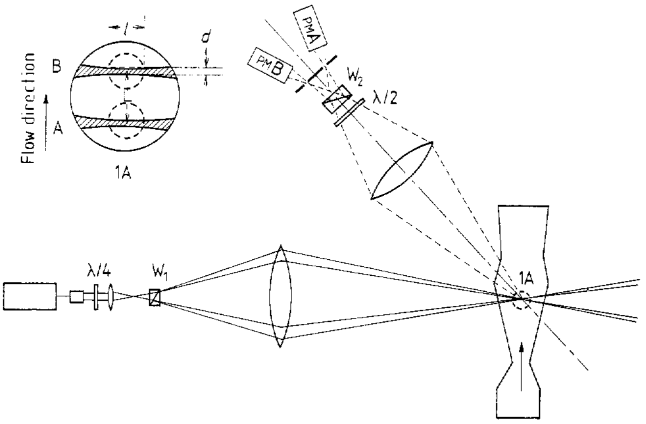

Figure 1 The experimental set-up.

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† Present address: California Institute of Technology, Noyes Laboratory, Pasadena, California 91125, USA.

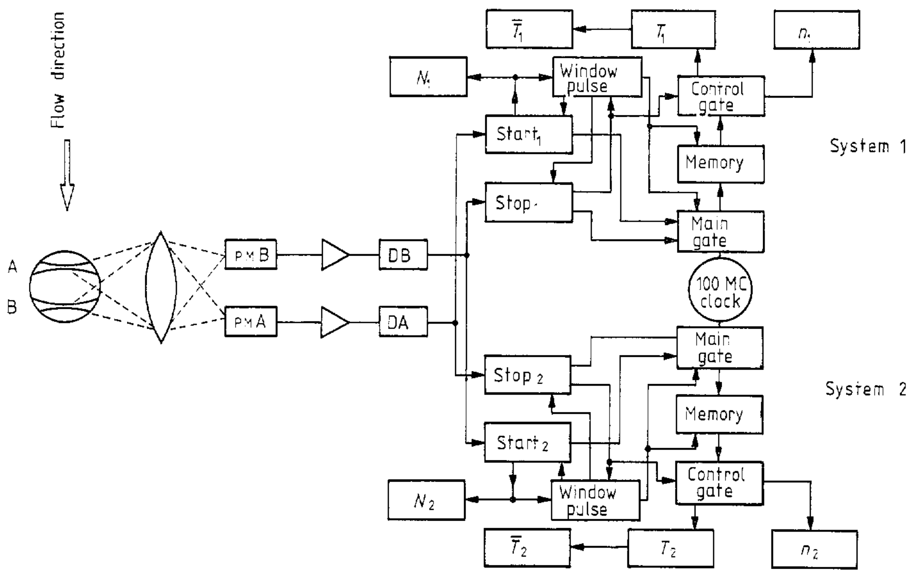

Figure 2 The electronic system.

(i) when a particle passes through the focus A, a signal enters the fast low-noise preamplifier and the discriminator DA will generate a start pulse;

(ii) this start pulse will trigger the starter 1, which then opens the main gate to let the clock signals (100 MC) enter memory 1 and increases the count of N_1 by 1;

(iii) at the same time the starter 1 lets the W_1 (window pulse generator) generate a 'window' pulse. The width of this pulse is T. Within this window the 'start' 1 is closed and the 'stop' 1 is opened by this pulse. If a stop pulse arrives during this period, it will close the main gate 1, stop the window pulse and open the control gate. Then the time count number, which is stored in memory 1, enters the time displayer T_1 and the count of n_1 is increased by 1;

(iv) If no stop pulse is received, the 'window' will automatically close after T. The back edge of the window pulse will make all the circuits return to their original state. The width T is always several times that of t which is the mean flight time;

(v) the operation of system 2 is the same as system 1.

According to the above mentioned logical structure the count ratio $n_1/N_1 = P_+$ shows the probability of the event that after a particle passes through the focus A there is at least one particle travelling through B within the window width T. The count ratio of system 2, $P_- = n_2/N_2$, shows the probability of the event that after a particle passes through the focus B there is another particle having travelled through A within time T. If the turbulence is homogeneous and the turbulent velocity fluctuation v' is smaller than the mean velocity of the fluid, then any particle which has crossed focus B cannot return to cross focus A.

There are five possible cases regarding the travel of particles as shown in figure 3. System 1 deals with events 1, 2, 3. Every event is statistically independent.

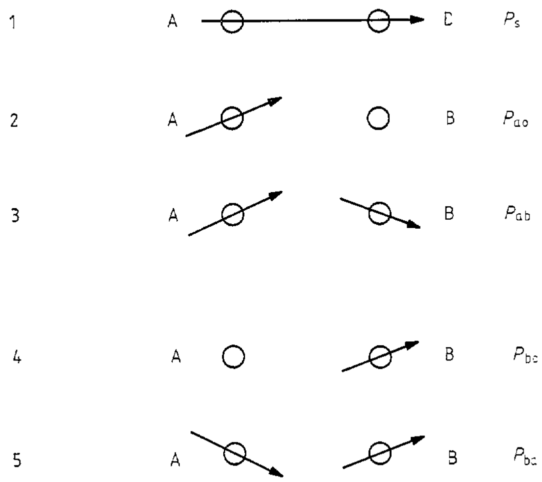

Figure 3 The five possible cases relating to the travel of the particles.

1 A particle travels directly from the first focus A to the second focus B within T. The probability of this event is P_s.

2 After a particle passes through focus A, no other particle crosses focus B during time T. The probability of this event is denoted by P_{ao}.

3 After a particle passes focus A, another particle crosses focus B during time T. The probability of this event is denoted by P_{ab}.

4 After a particle passes focus B, no other particle crosses focus A during T. This probability is P_{bo}.

5 After a particle passes focus B, another particle crosses the focus A during T. The probability of this event is P_{ba}.

For homogeneous turbulence, if the distance between the two foci, L, is small enough the turbulence parameters within $2L$ can be considered as constant. The average distance between particles is assumed far greater than L. The direction of flow is always from 'A' to 'B'.

In events 3 and 5 the particle which gives a 'start', and the particle giving a 'stop' signal are independent of each other under conditions of the above assumptions. Then we have

$$P_{ab} = P_{ba}. \tag{1}$$

For system 1, event 1 or event 3 can both increase the counts of n_1. According to the definition of P_+ we can write

$$P_+ = P_s + P_{ab} \tag{2}$$

For system 2, only event 5 can increase the counts of n_2

$$P_- = P_{ba} \tag{3}$$

From (1), (2) and (3) we obtain

$$P_s = P_+ - P_- \tag{4}$$

P_s/P_+ is the percentage of 'correct stop' signals in the measurements made by system 1.

By using equation (4), we can measure the probability of a particle travelling directly from the first focal point to the second by making use of the counts n_1, N_1, n_2, N_2. If the natural particle distribution is random, the time average will be homogeneous for steady flow (steady within the measurement time). The average of T_2 should be equal to half the window width $0.5T$. We define $\bar{T}_1$ as the arithmetic average value of T_1. The true average value of particle flight time between the two foci, t, can be determined from

$$\bar{T}_1 = tP_s/P_+ + T(P_+ - P_s)/2P_+. \qquad (5)$$

We then obtain

$$t = P_+\bar{T}_1/(P_+ - P_-) - TP_-/2(P_+ - P_-). \qquad (6)$$

From the above equation we know that if $T = 2\bar{T}_1$ or $P_- = 0$ the real flight time average value will equal $\bar{T}_1$. For a very stable laminar flow we can carefully adjust the window width to reach this point.

3 Result and discussion

We have used this method to measure the change of centre-line velocity of a transonic free air jet. The distance between two foci is 0.4 mm. P_+ was found to depend on the turbulent intensity and varied with the position of measurement point and the total pressure p_0. The value of P_+ changed from 0.1 to 0.3, P_- from 0.01 to 0.005 (Loh *et al* 1980). For example $P_+ = 0.1$, $P_- = 0.01$, from equation (4) we obtained $P_s = 0.09$, $P_s/P_+ = 0.9$. If width T is about $4t$, then $\bar{T}_1 = 1.1t$, the error between the arithmetic average $\bar{T}_1$ of system 1 and t then being 10% of the real flight time t. From this example we know that if only one system serves for measurement the arithmetic average method cannot give correct result. Schodl has taken the most probable value of T_1 as the average flight time t, which is a method to decrease the measurement error (Schodl 1976).

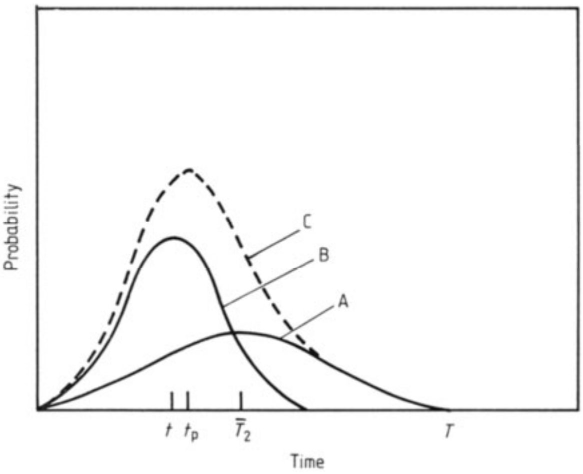

Figure 4 The distribution of measurement time values: A, T_2; B, real flight time; C, T_1.

The distribution of the time value is shown in figure 4. Curves A and C are the distributions of T_1 and T_2 values respectively. The most probable value of the distribution of T_1 is t_p. Here the probability only gives a measure of frequency of the events occurrence.

The real flight time distribution should be curve B which can be obtained from curve C minus curve A. The error between t and the most probable value t_p is about 1–2% in the above example.

Because N_1 and N_2 are between 10 000 and 50 000 s^{-1}, depending on the threshold value of the discriminator, so even for the worst situation $P_+ = 0.05$ we still have more than 500 data points of T_1 per second. These data are enough to use equation (6) for measuring the velocity.

The measurement results are shown in figure 5. When p_0 is greater than 2.2 atm, the centre-line mean velocity increases and decreases periodically in agreement with the Schlieren photographs of the jet. Figure 6 is a Schlieren photograph of the free jet when $p_0 = 5$ atm. When $p_0 = 2$ atm, the velocity in the jet core is constant, again in agreement with the calculation of one-dimensional isentropic flow. At this pressure the sonic speed value is obtained. All these results show that this new processing method is reliable. This method is simpler than digital correlation or multichannel analysis, because the real flight time can be obtained by using only the arithmetic average method.

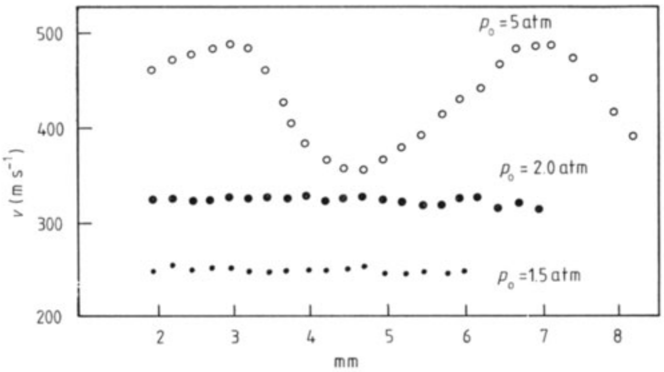

Figure 5 The change of centre-line mean velocity with distance from the exit.

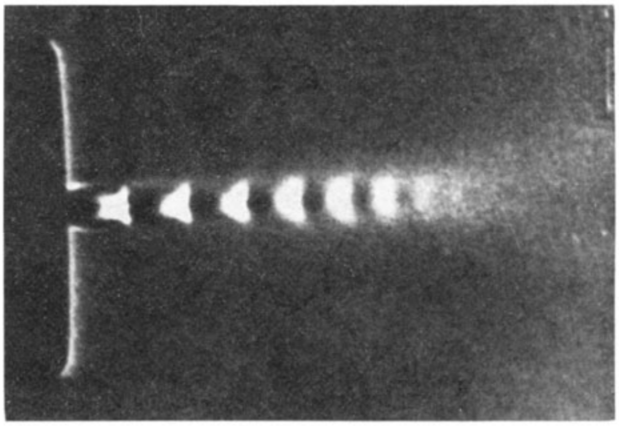

Figure 6 Schlieren photograph of free jet: $p_0 = 5$ atm, diameter of the nozzle exit = 3 mm.

Further points of significance in this method are as follows:

(i) the probability of the particle successively crossing two points is directly related to the turbulent diffusion coefficient and the Lagrange correlation coefficient. This method would be of help for studying turbulence diffusion and structure (Loh *et al* 1980);

(ii) this principle can be used to process the data of other two-point velocity detectors.

Acknowledgments

The authors are indebted to Professor H S Tan and Engineer Wang Yongguage, Yan Mingshan who supported this work strongly. Thanks are due to Professor Theodore Wu for suggestions to simplify the paper.

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