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ON-LINE MEASUREMENTS AND ANALYSIS OF HIGH TURBULENT AND REVERSE FLOW FIELDS

Al-KAYIEM H. H.*

ABSTRACT

As with most recent turbulence experimental researches, data are collected, stored and analyzed by digital computers. In this investigation, a wind tunnel measurement and analysis of flow field with high turbulence and recirculation is carried out. A sophisticated electronic/computer system is designed and implemented to permit data acquisition and on-line analysis either for in-situ calibration of the X-hot-wires or for measurement of high turbulence quantities and re-circulating flows. The technique is called Flying Hot-Wire probe system which is entirely controlled and operated by computer interfacing. The present paper involves description the interfacing of the measuring instruments with a PDP11-23 minicomputer. Also, it presents the digitizing technique to capture high turbulence and reverse flow. The hardware and the software which permit precise positioning of the measurement points in the flow field and the transfer of the flow field signals are presented. The procedure allows evaluation of the velocity components and the Reynolds stresses in axial and traverse directions. Validation test in still air and in uniform flow are conducted. The results are compared with those obtained from stationary hot-wires system. The in-situ calibration of the wires is successfully carried out with resulted normalized standard deviation of 0.7. The measurements error in the mean flow velocity is within 0.01% to 0.2%. The longitudinal turbulence intensity measured by the present technique is 1% compared with 0.8% measured by stationary hot wire. The results obtained are demonstrating that this is a successful technique for high turbulence intensity measurement

KEY WORDS

Turbulence, Hot wire anemometry, Signal analysis, On-line Data acquisition, Reynolds stresses.

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*Associate Professor, Mech. Eng. Dept., Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia, Hussain_kayiem@petronas.com.my

INTRODUCTION

The measurement and evaluation of the turbulent flows is the subject of huge amount of research works. It is not secret that the development of the measurement instrumentation and the data acquisition and analysis are almost carried out by the fluid dynamics researchers. The Laser Doppler Anemometry (LDA) is one of the advanced techniques that can be used, but they are costly and facing some limitation to be applied for all complex flow situations. Alternatively, the Hot-Wire Anemometry (HWA) may be used. But, the problem with the HWA is the lack in detecting the flow direction. A solution to the forward-reverse ambiguity is to ensure that measured velocity vectors attack the sensing element of the probe from one direction only. Also, it is preferable that the velocity vector lay within a narrow angle of attack to improve the analysis of the wire signals. Consequently, in order to obtain accurate results of the 2-D velocity components values, $U/\tilde{U}_f$, $V/\tilde{U}_f$ and the related fluctuations and Reynolds stresses, it is necessary that $\tilde{U}_f$ is sufficiently large. By moving the probe with a known velocity, $\tilde{U}_p$, with a value higher than the reverse flow velocity, this rectification problem can be avoided. This is the principle of the Flying Hot Wire (FHW).

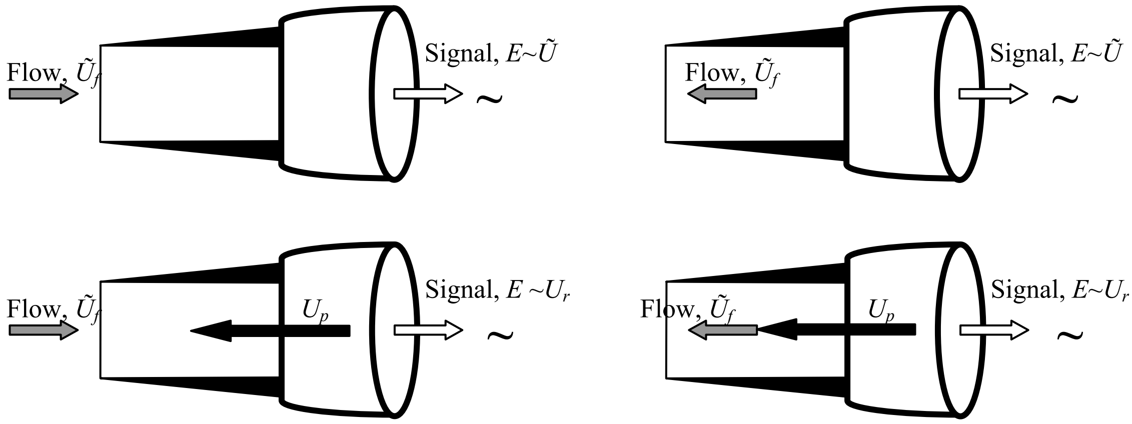


Fig. 1 ambiguity of the flow direction and it's avoidances by the FHW technique.

The criteria shown in Fig.1 is representing the most simple situation of the technique, where, the flow is normal to the wire and the measurement signal, E is corresponding directly to the mean flow velocity, $\tilde{U}_f$. If the flow attacks the wire with inclined angle, it should be involved in the analysis and this represents additional complexity. If the probe moves, this complicates the analysis furthermore. This is not the end of the story if looking for the two velocity components, U in the axial direction and V in the traverse direction. No way to obtain them without simultaneous measure of two signals at the same point using two inclined wires, usually called, X-hot-wire probe. The analysis will consist of four velocity components and five angles, all are varies from point to point in the flow field.

So far four types of the FHW system have been implemented and reported. The first one, in 1979, is at California Institute of Technology (C.I.T.) with circular flying path [1]. The second one is developed at Melbourne University, in 1983, with straight flying path [2], and the third one at imperial college, London, in 1984, with bean shape path [3]. An extensive review of the three techniques is given by [4] and [5].

The present paper describes the fourth FHW system which has been implemented in University of Bradford with bean shape path. The paper describes the interfacing and digitalizing of the system which is implemented and used to carry out analysis of the complicated flow fields, e.g. wakes, separated flow, jet interaction and high turbulence shear layer. Some of the results of the flow over high lift wings will be present as examples as well as some results of the turbulence structure behind back-word facing step. The system has been designed and constructed to satisfy the measurement of the two velocity components and the resulting shear stress using X-hot-wire probe.

FLYING HOT WIRE SYSTEM

Generally, an advantage of a FHW system is it permits, during a single traverse (sweep), data acquisition for many points along the flying path rather than at a single point. In this way, more representative information about the flow field as a whole can be gathered since the effect of variation in the flow conditions, hot-wire drift etc. are distributed more uniformly in space, than if measurements are taken sequentially, point by point, as in the case of static probe.

φ: the fly wheel position angle
$L = (a^2 - r^2 \sin^2 \varphi)^{0.5}$
ψ: the probe position angle

r = 60 mm (Radius of rotation)
a = MN = 160 mm (Upper part of the flying arm)
b = NO = 410 mm (Lower part of the flying arm)
c = OP = 146.8 mm (Probe + mounting tube)

TDC: Top Died Center
BDC: Bottom Died Center

y_p: the vertical axis of the probe path plane
$x_{p,}$: the horizontal axis of the probe path plane

Start M: start sending measurement signals
Stop M: stop sending measurement signals

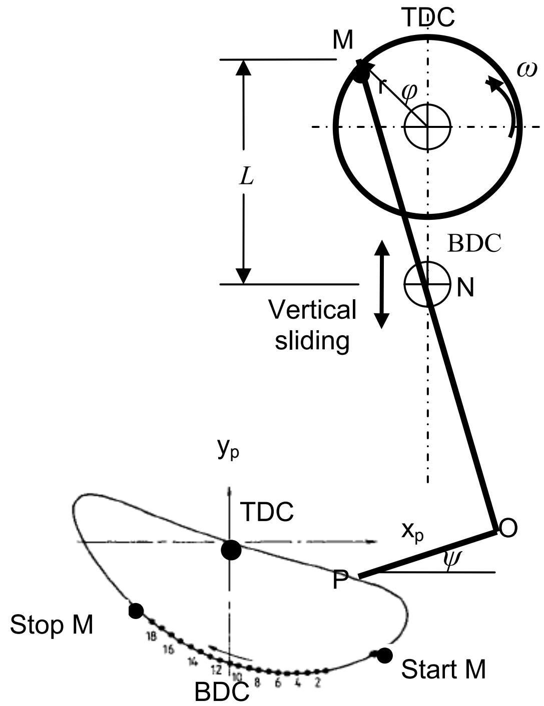


Fig.2. Schematic diagram of the FHW mechanism and the resulting probe path.

A four bar mechanism is selected for this FHW system to provide the “bean shape” of the probe path inside the flow field. The schematic diagram in Fig. 2 shows the geometry of the mechanism and the resulting probe path corresponding to complete revolution of the fly wheel. The fly wheel is coupled to an electric motor. The motor is coupled to an encoder which having resolution of EN=500 pulse/ revolution. This allow measurement of the fly wheel position angle, φ.

The Probe Position and Velocity

To obtain accurate results of the flow characteristics, it is necessary that the coordinates of the center point of the flying probe, i.e. the cross point of the two wires; x_p and y_p are known at any instant of measurements together with the corresponding probe velocity. Referring to the geometrical shown in Fig. 2, it follows that

$$x_p = -r(b/a)\sin\varphi + (c/a)L - c \tag{1}$$

$$y_p = a + b - r + r\cos\varphi - (1 + (b/a))L - r(c/a)\sin\varphi \tag{2}$$

where, the variable distance, L shown in fig. 2 is:

$$L = \left[a^2 - (r\sin\varphi)^2\right]^{0.5} \tag{3}$$

The probe velocity components U_p in x-dir. and V_p in y-dir. are obtained by differentiation of equations 1and 2 with respect to time t and setting the differentiation term $d\varphi/dt = \omega$, getting:

$$U_p = \frac{dx_p}{dt} = \omega r\left(\frac{b}{a}\cos\varphi + \frac{cr\sin 2\varphi}{2aL}\right) \tag{4}$$

$$V_p = \frac{dy_p}{at} = \omega r\left[\left(1 + \frac{b}{a}\right)\times\left(\frac{r\sin 2\varphi}{2L}\right) - \sin\varphi - \frac{c}{a}\cos\varphi\right] \tag{5}$$

and, the resultant probe velocity, $\tilde{U}_p$ and it's direction, β, are:

$$\tilde{U}_p = \left(U_p^{\ 2} + V_p^{\ 2}\right)^{o.5}$$

$$\tilde{U}_p = \left(U_p^2 + V_p^2\right)^{0.5} \qquad \textit{and} \qquad \beta = \arctan\left(V_p / U_p\right) \tag{6}$$

The value of the angular velocity, ω is obtained from:

$$\omega = \frac{\Delta\varphi}{\Delta t} \qquad (7)$$

It could be noticed that the dominant variable to evaluate the probe instantaneous coordinates and velocities is the fly wheel position angle, φ. It can be measured by monitoring the encoder pulses which allows the evaluation $\Delta\varphi$, where, $\Delta\varphi = 2\pi/N$ (rad) is the angular displacement between two pulses of the encoder. With EN = 500 pulse/revolution, the angular resolution becomes 0.72°/pulse. The corresponding time interval, Δt is measured by electronic circuit consisting of two multiplexer, two counters and 10 MHz reference oscillator. This circuit is designed originally by [4] and modified to satisfy the present applicant.

Analysis of the X-Hot-Wire Signals

The type of hot wire used in is DANTEC-plated X probe (55p51). Using the notations in Fig.3, the wires are responding to the velocity vector in the flow field, $\tilde{U}$ as seen by the probe, and the measured velocity components, U' and V' are evaluated in the probe stem coordinates x' and y'. Since the probe moves with instantaneous velocity, $\tilde{U}_p$, all the analysis of the wires signals should involve the flow velocity, the flow direction, the probe stem velocity and its direction. It could be said that the wires signals are responding to the instantaneous relative velocity, $\tilde{U}_r$, which has the components, U_r and V_r, and analyzed in the probe-stem coordinates as U'_r and V'_r. Based on the notations of Fig.3, the relative velocity components are:

$$U_r = U'_r \cos\psi - V'_r \sin\psi \qquad (8a)$$

$$V_r = U'_r \sin\psi + V'_r \cos\psi \qquad (8b)$$

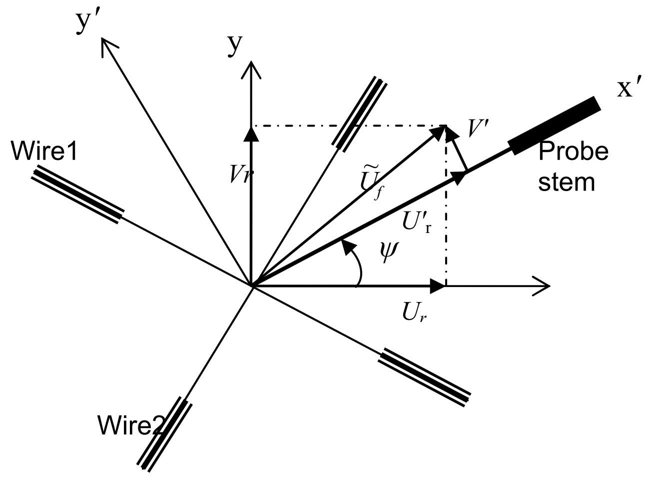


Fig. 3. Components of the relative velocity in probe-stem and space-fixed coordinate system

The determination of U'_r and V'_r is described in details by [5] and [6]. Using the sum and difference method [7], in conjunction with the k calibration model suggested by [8] and the optimization technique suggested by [5], the wires signal $E1$ and $E2$ are:

$$E_1^2 = A_1 + B_1 V_{eff1}^{n_1} \qquad (9a)$$

$$E_2^2 = A_2 + B_2 V_{eff2}^{n_2} \qquad (9b)$$

and

$$V_{eff1} = \widetilde{U}_r (\cos^2\alpha_1 + k_1^{\,2} \sin^2\alpha_1)^{1/2} \qquad (10a)$$

$$V_{eff2} = \widetilde{U}_r (\cos^2\alpha_2 + k_2^{\,2} \sin^2\alpha_2)^{1/2} \qquad (10b)$$

where, α_1 and α_2 are the yaw angles of wire1 and wire2 respectively. The calibration constants, A_1, B_1, n_1, k_1 for wire1, and A_2, B_2, n_2, k_2 for wire2 are evaluated by in-situ calibration and optimization of the experimental raw calibration data as detailed by [6].

From the set of equations 4, 5, 8 and 9, the flow velocity components predicted as:

$$U = U_r + U_p \qquad (11) \qquad and \qquad V = V_r + V_p \qquad (12)$$

The mean flow velocity magnitude, $\tilde{U}_f$ and its direction, θ_f are

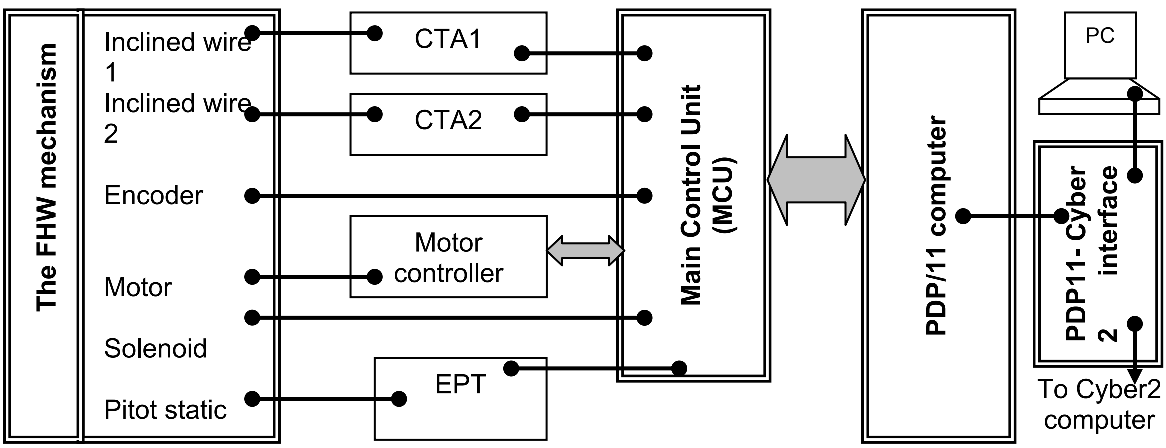
$$\tilde{U}_f = (U^2 + V^2)^{0.5} \qquad (13) \qquad and \qquad \theta_f = \tan^{-1}(V/U) \qquad (14)$$

The above analysis is for one sample record. For N samples, the mean values of the flow velocity component will be used instead of the single sample values as will be explained later.

THE INTERFACING ARRANGEMENT

The sequence of data transfer is starts firstly from the FHW mechanism to the Main Control Unit(MCU) then, the later is interfaced with computer system. The interface allows the following function to be achieved:

- Signal, $E1$ and $E2$ are transferred from Wire1 and wire2 to the constant temperature anemometers, CTA1 and CTA2 respectively, then to the MCU as analogue signals. The MCU consists of three A/D converters. A/D2 and A/D3 are used to convert the analogue wires signals to digital and transfer them to the computer in Volts. The stored values are processed to determine the flow field information.
- Signals are transferred from the encoder as train of pulses to a "velocity board" which contains two counters, multiplexer and a 10 MHz reference oscillator. The multiplexer sends alternating readings from the counters to an assigned location in the computer's memory. Obtaining the number of pulses of cycles measured during one encoder pulse, and dividing by 10 MHz, the t is measured in seconds.
- Signals transferred from the electronic pressure transducer to the MCU in analogue form. A/D1 in the MCU converts and transfers them to the computer memory.
- Feed back command signals are generated from the MCU to the 'motor controller' to control the motor operation sequence (switch on and switch off the motor, start sending measurement signals and stop sending measurement signals)
- Feed back command signals are generated from the MCU to activate a solenoid in the breaking unit of the fly wheel to assist in deceleration of the motor and reduce the stopping time.



CTA: Constant Temperature Anemometer, EPT: Electronic Pressure Transducer, MCU: Main Control Unit

Fig. 4 Schematic diagram of the interfacing logic

The above signal manipulation is ended with results related to the flow field information. These results are stored in the PDP11 computer memory. PDP11- Cyber2 interface is another interface designed and used to transfer the results from the PDP11, in the laboratory, to either the main frame Cyber2 in the computer center or to a PC computer in the lab. The results are then processed in the main frame for final presentation. The logic of the entire signal transformation is shown in the schematic of Fig.4.

This FHW-MCU-PDP11computer interface is representing the hard ware part of the technique. A program written in FORTRAN77 language is representing the software part of the technique. The program consists of master program with many subroutines and subprograms written in the machine language to control and operate the various units of the computer as described by [5]. The sequence of the technique operation is shown in Fig.5.

EVALUATION OF THE TURBULENCE QUANTITIES

The turbulent motion of flowing fluid is a random phenomenon. Consequently, for an ensemble of similar experiments, the velocity existing at a given point in space and time will fluctuate in a random manner and for this reason statistical methods are used to characterize the turbulence. For stationary random process, the time average velocity $U(t)$ does not vary with time and the argotic hypothesis states that the time average converges to mean value as the averaging time grows and that this mean value is equal to the corresponding ensemble average value. In practice, most random processes, including separated flows, are stationary.

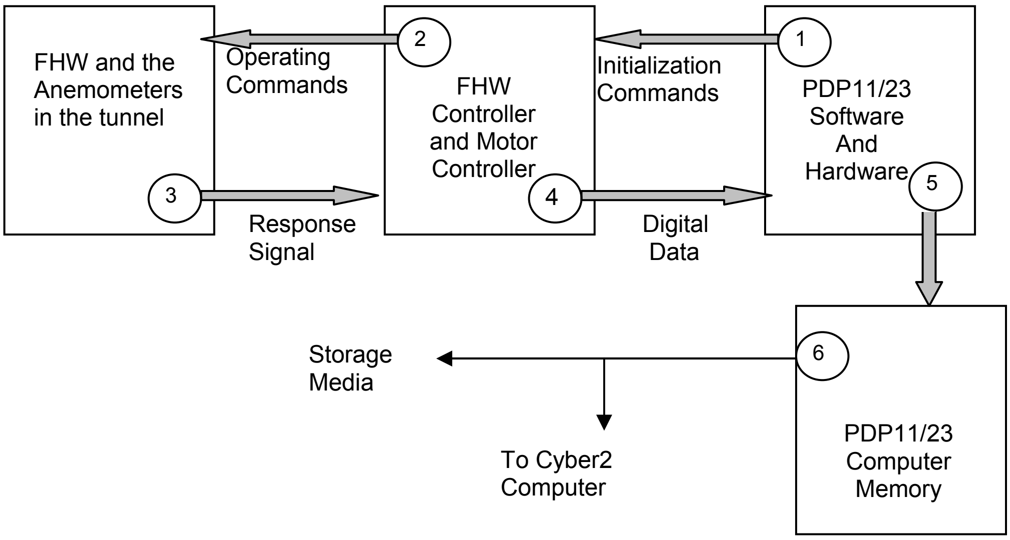


Fig.5. Basic Principle of FHW System Control, Operation and Data Acquisition.

The time average over a specific sample record for time period, T is defined as:

$$\overline{U} = \lim_{T\to\infty} \frac{1}{T}\int_0^T U(t)dt \qquad (15)$$

While, the ensemble average for number of sample record, N (so-called sampling size), is defined as:

$$\overline{U} = \lim_{N\to\infty} \frac{1}{N} \sum_{1}^{N} U(t) \qquad (16)$$

Ensemble Average of the Mean Velocity

For N realization of a random process taken in sequence of equal time intervals between each sample record, the mean value at any time t from equation 16 can be evaluated as:

$$\overline{U} = \frac{1}{N} \sum_{i=1}^{i=N} U_i \qquad (17)$$

The quantity $\bar{U}$, calculated from equation is unbiased estimate of the true value of $\bar{U}$. In the present study, the time interval between consequents sample records is 10 sec. This large time interval is selected as resting time for the probe outside the measuring zone to insure steadiness of the flow without disturbance from the presence of the probe in the measuring zone. The sample size (later referred to as NS) is selected based on prior evaluation using a confidence level of 95% and it has been claimed that N=200 is sufficient for such confidence level [5]. Consequently, the two mean velocity components of the flow, $\overline{U}$ and $\overline{V}$, at a measuring point are:

$$\overline{U} = \frac{1}{200} \sum_{i=1}^{i=200} U_i \qquad (18a) \qquad \text{and} \qquad \overline{V} = \frac{1}{200} \sum_{i=1}^{i=200} V_i \qquad (18b)$$

And the flow velocity vector is predicted using equations 13 and 14.

Reynolds Convention and Variances

The fluctuation in the axial direction, u of the velocity component, U and the fluctuation in the traverse direction, v of the velocity component, V were evaluated as:

$$\overline{u^2} = \frac{1}{NS-1} \sum_{i=1}^{i=NS} \left[U_i - \overline{U}\right]^2 \qquad (19)$$

$$\overline{v^2} = \frac{1}{NS-1} \sum_{i=1}^{i=NS} \left[V_i - \overline{V}\right]^2 \qquad (20)$$

and the covariance, uv as:

$$\overline{uv} = \frac{1}{NS-1} \sum_{i=1}^{i=NS} \left[U_i - \overline{U}\right]\left[V_i - \overline{V}\right] \qquad (21)$$

where the sampling size, NS=200.

The quantities of the fluctuations, $\overline{u^2}$ and $\overline{v^2}$ are representing Reynolds stresses in x and y directions respectively. The covariance $\overline{uv}$ is representing the shear stresses in the turbulent flow. In studies of turbulence, the turbulent intensity of two dimensional flows is often defined as:

$$T.I. = \left[\frac{1}{2}\left(\overline{u^2} + \overline{v^2}\right)\right]^{1/2} \qquad (22)$$

And the corresponding relative intensity, as:

$$R.T.I. = \frac{T.I.}{\widetilde{U}_f} \qquad (23)$$

RESULTS AND DISCUSSION

The FHW system described in this paper has been used to characterize the separation bubble in two applications. Firstly, the technique is applied to trace the flow structure on backward facing step with relatively large scale model. The second application is to study the separated flow from high lift wing model. The subject of the present paper is not to present the results on the above studies as its main objective is focusing on the signal processing for turbulence measurement. The validation of the procedure is achieved by comparing with stationary hot-wire results and standard Pitot static tube. The measurement accuracy of the flow mean velocity is carried out at 4.7 m/s with error of 0.2% and then at 19.7 m/s where the error is 0.01%. The longitudinal turbulence intensity measured by the present technique is 1% compared with 0.8% measured by stationary hot wire. This level of accuracy is excellent for high turbulence measurements and to conduct wind tunnel experimentation. The calibration accuracy of the hot-wires are less than 0.7% and the selection of the sampling size is with 95% level of confidence.

Back Ward Facing Step Results

The first sample of measurement using the described FHW and the related turbulent analysis is application on back ward facing step. Sample of results in Fig.5 is showing the measured axial stresses as $\overline{u^2}/U_\infty^2 \times 10^3$. The results are in a good agreement with previous investigation as presented in Table 1. The stresses are high in the surroundings of the separation bubble. Previously, there is a believe that the highest stresses are occurring inside the separation. Another significant finding from the current experimentation that the shear layer above the bubble is not stable and it is fluctuates within the mixing region of the incoming main flow and the re-circulated flow.

The present investigation is different from the previous ones in that it was carried out using a larger step model with higher step height. It is difficult to compare various data tests due to the effect of different initial conditions. However, as suggested by [9], the variation in the inlet conditions is reflected on large extends only in different reattachment length. Therefore, for comparison purpose, data may be compared in

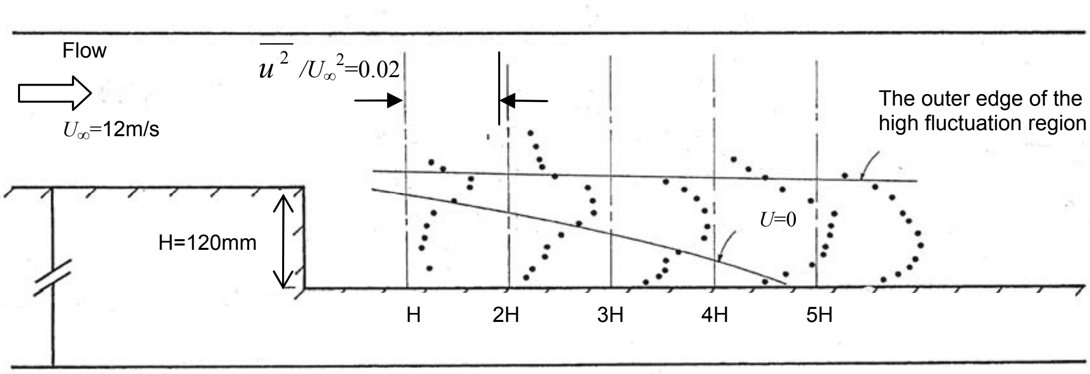


Fig.5. Profiles of the measured axial stresses ($1000\overline{u^2}/U_\infty^2$) at different locations in the reverse flow region

normalized form using non dimensional length, $\hat{x}=(x-x_r)/H$, where x_r is the location of the reattachment of the separated flow. A further complication in comparing different investigations is that different measurement techniques are used in various investigations. In spite of that, all the experimental results are showing that the reattachment of the separated flow is occurred at about 5H to 6H. Furthermore, the axial stresses, $\overline{u^2}/U_\infty^2$ are within the same level in all of the experimental results, which is 0.03 to 0.04. Later on, the same equipments and technique described in this paper has been used by [10] to extend the investigation to cover larger measurement area and to improve the accuracy of the results. Detailed discussion of the results of the backward facing step of the current study is presented and compared with CFD analysis by [11].

Table.1. Comparison with further experimental results

Investigator (s)	configuration	Measuring technique (s)	H mm	U_∞ m/s	Re_H x10^4	$\overline{u^2}/U_\infty^2$ x10^3	X_r / H
Eaton et al. []	wind tunnel	Pulsed wire, Thermal tuft	50.8	13	4.1	41	6→6.5
Etheridge and Kemp []	water tunnel	LDV	13.5	0.276	0.37	36	5.1
Tropea []	water tunnel	LDV	40	0.84	0.28	30	5.8
Current case	wind tunnel	FHW	120	12	9.7	31	4.5→5

Aerofoil Results

Sample of measurement results obtained from NACA 4412 are shown in Fig.6. All of the 2-D flow field parameters are predicted involving the two velocity components, the mean velocity magnitude and direction and the three Reynolds stresses. The axial stresses are presented in Fig.6 as contour plots. The measurements are covering the

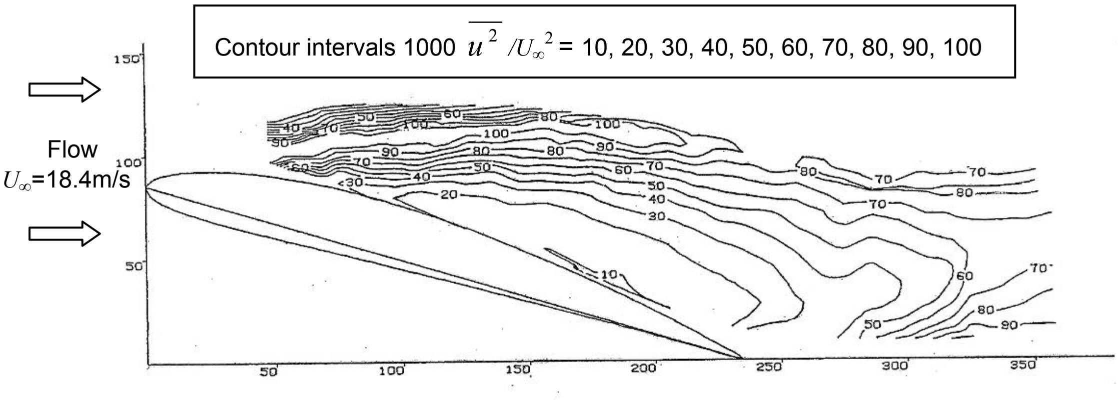


Fig.6. Contour plots of the measured axial stresses $\overline{u^2}$ at $Re_c = 0.36x10^6$

reversed flow region, the shear layer region and the near wake region. As in the case of the results of the backward facing step, the stresses have their maximum values in the surrounding of the separation bubble, not inside the bubble. Near the surface, the axial stresses $\overline{u^2}/U_\infty^2$ are within 0.01 to 0.02. In the interaction between the free stream and the reversed flow, they reach the level of 0.1. This is close to the experimental results reported by [1].

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