# Development of Single Sensor Fast Response Pressure Probe

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## Abstract
Multi-sensor fast response pressure probes are often used in turbomachinery investigations. However the size of multi-sensor probes are often larger than is ideal. Therefore, a single sensor pressure probe that has sufficient sensitivity for 3D flow field will bring a great benefit for turbomachinery investigators.
Several types of probes were designed and tested with enlarged models in a wind tunnel. Both static and dynamic response has been investigated. The correlation between the shape of the probe and its yaw and pitch sensitivity has been investigated through measurements of pressure distribution on the enlarged models and through some flow visualizations.
Dambach and Hodson(1998) proposed a new method of data reduction for a single sensor pressure probe. In this work, a single sensor pressure probe with the shape of a triangular prism was fabricated and tested with success in a radial flow turbine where the flow field was mainly 2D. The probe was shown to have only yaw-sensitivity while pitch-sensitivity is also important in the survey of three dimensional turbomachinery flows.
In this paper, ten different enlarged probe models were designed and tested in order to address the issue of pitch-sensitivity of single sensor pressure probes. Through static measurements, the dependency of pitch sensitivity on

(1)Probe shape(Square, Cylinder, Triangle)
(2)Slanted Face Probe Tip Design

were investigated respectively. Having assessed all the designs based on the static experiment, the dynamic effects were investigated for selected designs.
The obtained results indicate that a slanted face and appropriate probe tip design increase pitch sensitivity of the single sensor probe to acceptable levels for a successful probe calibration and application of data reduction procedures. Finally the cylindrical probe design appears to be less affected by dynamic and unsteady flow effects in the range of flow conditions tested.

## Nomenclature

| | |
|---|---|
| Re | Reynolds Number |
| St | Strouhal Number |
| N | number of orientation |
| P | pressure |
| S | pitch sensitivity |
| V | velocity |
| f | frequency |
| d | diameter of probes |
| $C_p$ | pessure coefficient ($=(P-P_s)/(P_t-P_s)$) |
| $\alpha$ | yaw angle |
| $\beta$ | pitch angle |
| $C_p(\alpha,\beta)$ | $C_p$ at yaw angle of $\alpha$ and pitch angle $\beta$ |
| $\rho$ | density |
| r | ratio |
| w | width |

**Sub- and Superscripts**

| | |
|---|---|
| s | static |
| d | dynamic |
| t | total |
| cal | calibration |
| mes | measured |
| y | yaw |
| p | pitch |
| abs | absolute |
| rel | relative |
| wk | wake |
| i, j | index |
| * | non-dimensional value |
| b | moving bar |
| freq | freqency |

## 1. Introduction

A number of types of probes have been used in turbomachinery investigations. A lot of investigators have employed single sensor hot wire anemometers in multiple positions to determine the mean velocity vector, turbulence intensities and Reynolds stresses. Likewise, many have used multi-sensor fast response pressure probes to measure an unsteady flow field. Unfortunately, they are often larger than is ideal (e.g. 2.5 to 6 mm, see Grossweiler et al (1990), Cherret et al, (1992)) for many facilities. While these probes may provide data of acceptable quality in relatively large-scale facilities, such facilities are rare. On the other hand, single sensor pressure probes can be typically made to be a half to a third of the size of multi-sensor probes. Furthermore, because a single sensor is employed, the calibration is simpler and changes in calibration due to ambient changes are easier to accommodate. In addition, the complexity of manufacturing and its costs are reduced.

One significant disadvantage to the use of single sensor pressure probes has been the increase of the running cost compared with multi-sensor pressure probes. Recently, Dambach and Hodson(1998) proposed a new method of data reduction, by which single sensor pressure probe has become more attractive in combination with the least squares method.

For single sensor pressure probes, the shape of a probe plays a very important role in its sensitivity because there is only one sensor on it. So, deep understanding of the flow around it and an appropriate flow control by its shape are needed to increase sensitivity.

## 2. Static Enlarged Model Test

In order to investigate the dependency of pitch and yaw sensitivity on probe shape, enlarged model test has been conducted in a wind tunnel. Ten models were tested here of which geometries were based on simple shape. Not only pressure distribution on the sensing face of each model was measured, but also some flow visualizations were conducted in a smoke tunnel. The nominal size of each model is 30mm, which is more than fifteen times larger than real miniature probe.

Main Parameters

(1) Probe Shape (Square, Triangle, Cylinder)
(2) Slanted Face Probe Tip Design (Slanted Angle)

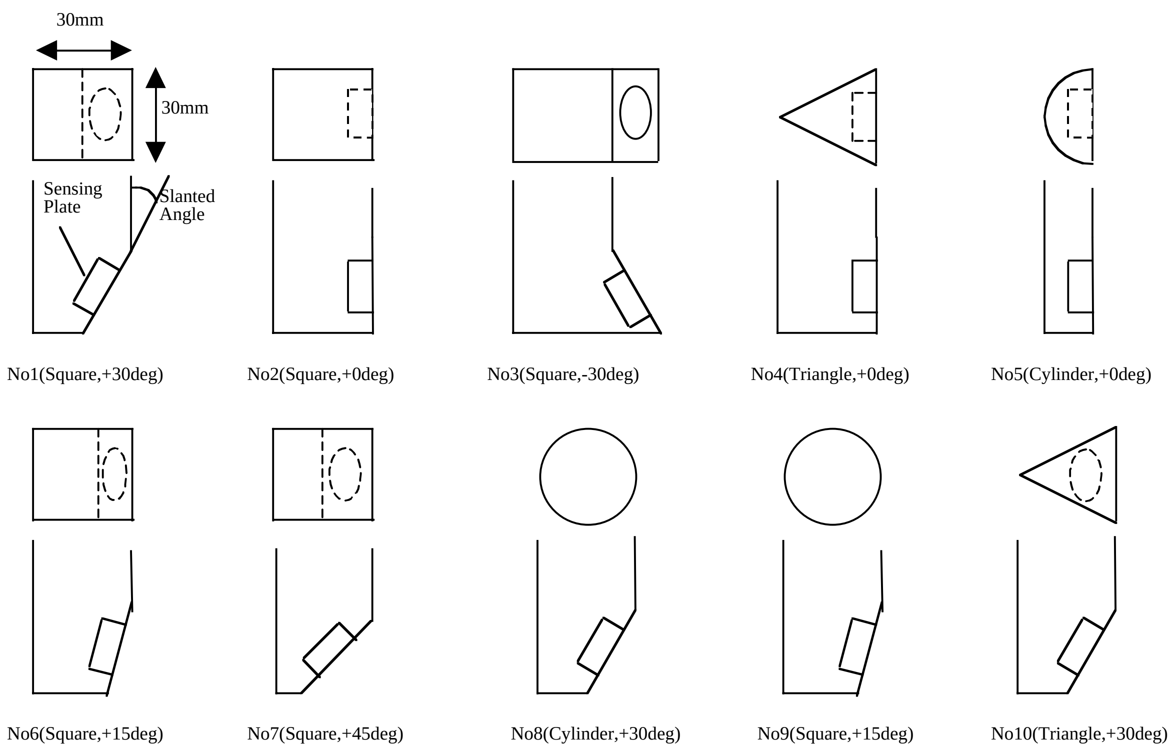


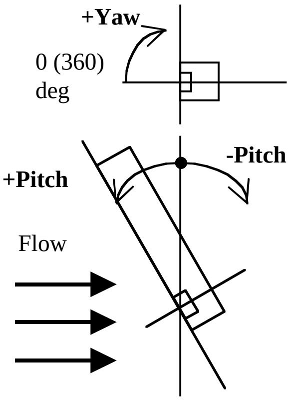

Fig.2-1 Tested Probe Geometries

**Experimental Setup**

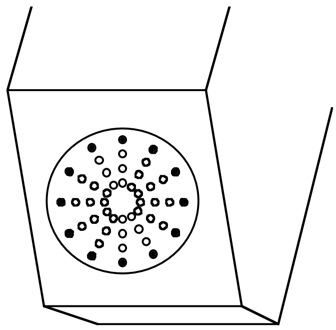
Enlarged models were fixed at the exit of a wind tunnel. The ratio of hydraulic diameter of its exit size to probe size is about thirty, which is enough large to regard the flow as a free stream. Two stepping motors were employed to move probe models for both yaw and pitch direction, keeping the probe head at the centre of the wind tunnel. A sensing plate with the diameter of 20mm was designed. It has 48 small holes on it and each of them was connected to a scanivalve with a tube (0.58mm ID). All the driving and measuring devices were controlled by Lab-View via RS232 daisy-chain.

Definition of pitch and yaw angle is shown in Fig.2-2. Pressures of all holes and static pressure and dynamic pressure of the flow were automatically measured at each yaw-pitch position. Thus $C_p$ distribution on the sensing plate could be presented for each position. (Fig.2-3)

Commercially a miniature pressure sensor is provided with a screen which gives robustness to it. As for Kulite pressure sensors, they can provide us with two kinds of screen, namely B screen and M screen. B screen has 12 holes arranged around a circle close to the outer diameter. The representative data on sensing plate is based on the averaged value of holes on B screen arrangement. This means only the data around a circle close to the outer diameter was used for data processing, assuming that the pressure on the sensor becomes the average of the pressure of each screen hole.




Hole arrangement on the sensing plate



● shows B screen hole arrangement

Fig. 2-2 Defintion of pitch and yaw angle

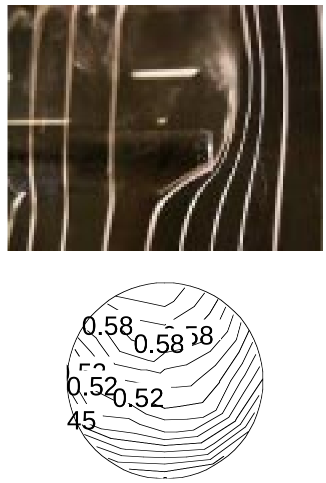



Fig.2-3 Flow around a probe (upper) and $C_p$ distribution on sensing plate (lower)
(Probe No.8 at $\alpha$,$\beta$=0)

**Experimental Condition**

Experimental condition is shown in Table 2-1. The diameters of single sensor probes employed for fast response measurements in turbomachines are expected to be of the order of 1<d<2(mm). Free stream velocities V ranging from 100 to 300m/s, then Re becomes

$$\mathrm{Re} = \frac{V\,d}{\nu} = 10{,}000...120{,}000$$

In the experiments, the wind velocity was set to 20 or 40m/s for enlarged models with nominal size of 30mm, considering the accuracy of the pressure measurement. Reynolds number of 40,000 or 80,000 was chosen which includes most of the range to be used for a single sensor pressure probe.

| | CASE 1 | CASE 2 |
|---|---|---|
| | Basic Condition | Re dependency test |
| Wind Velocity (m/s) | 20 | 40 |
| Yaw angle (deg) | 0 to 360, every 18 deg | |
| Pitch angle (deg) | -60 to 60, every 15 deg | |
| Reynolds Number | 40,000 | 80,000 |
| Tested Probe Model | All models(No1 to No10) | Only for Probe No.1 |

**Table 2-1 Experimental Condition**

## Application of the "least squares method" and the definition of "Pitch sensitivity" for a single-sensor pressure probe

**"Least Squares Method"**

As for a single sensor pressure probe, there are 4 unknown parameters. They are static pressure, dynamic pressure, yaw angle and pitch angle. The least squares method aims to minimize the quantity

$$\left\langle \chi^2 \right\rangle = \sum_{i=1}^{N} \left(P_i - \left(P_d C_p(\alpha,\beta) + P_s\right)\right)$$

In the real measurement, a probe will be inserted into flow then rotated around its stem. The measured pressure at each yaw position would be like Fig.2-4. On the other hand, the calibration data would be like Fig.2-5. By comparing them the each other by the least squares method, all the unknown parameters can be calculated.

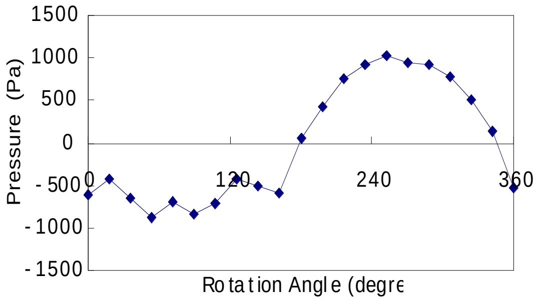



Fig.2-4 A sample of Measured Data

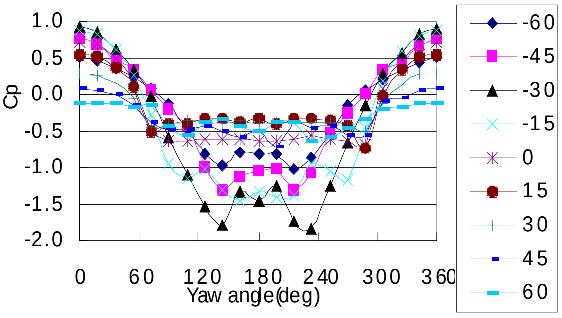



Fig.2-5 A sample of Calibration Data

**"Definition of pitch sensitivity for a single-sensor pressure probe"**

When developing a single sensor pressure probe, the "sensitivity" need to be quantified and evaluated with calibration results in a wind tunnel.

In data processing with the least squares method, the measured data will be shifted, scaled and offset to find the minimum value $<\chi^2>$ between measured pressure and the calibration data.

In the calibration data, therefore, the minimum difference between any of two calibration curves of different pitch angle, after being appropriately shifted, scaled, and offset, shows the pitch sensitivity. In other words, the difference of "Shape" of calibration curves shows the "pitch sensitivity".

Here only the data of yaw angle from 0 to 72 and from 288 to 360 degrees were used in order to reduce the dependency of the sensitivity on flow separation. Generally the flow separation phenomena is strongly dependent on Reynolds Number. Probes should be designed to be as less affected by Re number as possible, otherwise the quality of the measurement might be catastrophically deteriorated, especially when it's used in the flow of different Reynolds Number from that of calibration.

Fortunately, in the use of the least squares method of data processing, it is possible to use only the data which may be less affected by flow separation. Accordingly, only the limited range of data was used for the least squares method of data processing. In fact, there was another possibility to use those from 0 to 90 and from 270 to 360 degrees. However, through careful investigation of the results, the former is better than the latter as far as all the probes tested here are concerned. This result seems reasonable because it is commonly known that the flow around a cylinder begins to separate at 83 degrees. Thus, not only the aerodynamic shape of a probe, but also the data processing algorithm is important for the quality of measurement for a single sensor pressure probe.

The pitch sensitivity can be defined in the following way.

Defining a new parameter $C_p^*$,

$$C_p^*(\alpha,\beta) = \frac{(C_p(\alpha,\beta) - C_p(\alpha_1,\beta))}{(C_p(0,\beta) - C_p(\alpha_1,\beta))}$$

$\alpha_1$ is the lower anchor of yaw angle in normalizing the "shape". Here is used 72deg for $\alpha_1$ in the calculation of sensitivity for the reason mentioned.

Then the sensitivity S is expressed as,

$$S(\beta_1,\beta_2) = Min\left\langle \lambda^2 \right\rangle$$

Where

$$\lambda^2 = \int_0^{\alpha_1} \left[ C_p^*(\alpha,\beta_1) - \{A C_p(\alpha,\beta_2) + B\} \right]^2 d\alpha$$

| | |
|---|---|
| $S(\beta_1, \beta_2)$ | pitch sensitivity between the pitch angle of $\beta_1$ and $\beta_2$ ( $\beta_1 > \beta_2$ , $S(\beta_2, \beta_1) = S(\beta_1, \beta_2)$ ) |
| A | stretch factor |
| B | offset factor |

The new factors A and B are given using the least squares method. Hence the sensitivity is calculated for each probe tested.

**Results**

Fig.2-7 shows the sensitivity contour calculated between two $C_p$ curves at different pitch position of the probe models. So both the vertical and horizontal axis show.

**Effects of Slanted Face Angle on pitch sensitivity**

The results for square type probes indicate that slanted face design increases sensitivity. Probe No.1(+30deg) design seems best. Probe No.7(+45deg) also seems good. However, this is only at the pitch angle less than 0 degree, because $C_p$ is less than 0 at all range at the pitch angle more than 0 degree. This is also the case for the other types of probe. As for the cylindrical probe, Probe No.8(+30deg) has slightly better sensitivity than Probe No.5(+0deg) and Probe No.9(+15deg). For triangle probes, Probe No.10(+30deg) has better sensitivity than Probe No.4(+0deg). In conclusion, slanted face design increases pitch sensitivity and the best slanted angle is +30 degrees regardless of probe type.

As for Probe No.5(+0), all the curves converge;70deg;(Fig.2-6(1),Fig.2-6(2)) In this case, the shape of each curve is close to one another and this means there is less sensitivity. On the other hand, as the slanted angle increases, each curve changes its shape which results in the increase of sensitivity. (Fig.2-6(3),(4)) The same thing can be said for the other types of probe(Square and Triangle) Slanted face design can change the "shape" of calibration curves and this results in the increase of pitch sensitivity regardless of probe type.

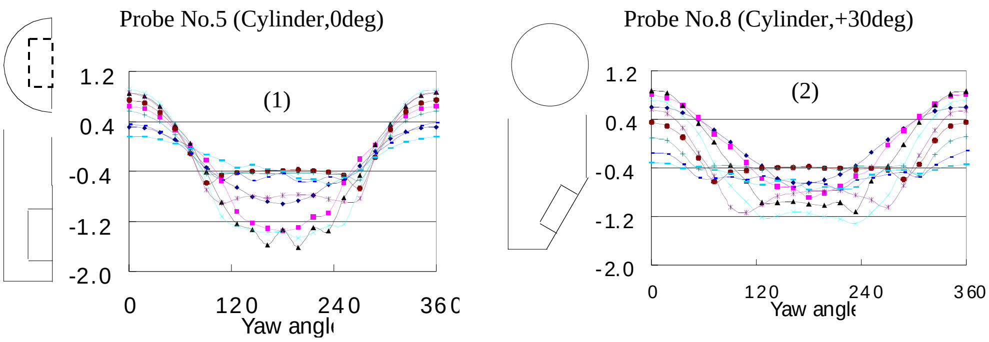



Fig.2-6 $C_p$ vs yaw angle of different slanted angle designs of cylindrical probe

**Effects of Reynolds Number on pitch sensitivity**

For the range of Re numbers under investigation, there doesn't seem to be any Reynolds Number dependency on probe No.1(+30deg). So, the experimental condition was enough reasonable to discuss the sensitivity of each sensor at relatively high Reynolds Number.

**Comparison of Probe Type**

Comparing sensitivity contour of the +30deg slanted face designs with each other (No1 with No8 and No10), No8 and No10 seem to have good sensitivity at high pitch angle. No1 and No8 seem to have good sensitivity at low (negative) pitch angle. Thus, No8 seems to have the best sensitivity at wide range of pitch angle.

In summary, the present results indicate that the best probe design is Probe No8(Cylinder,+30deg).

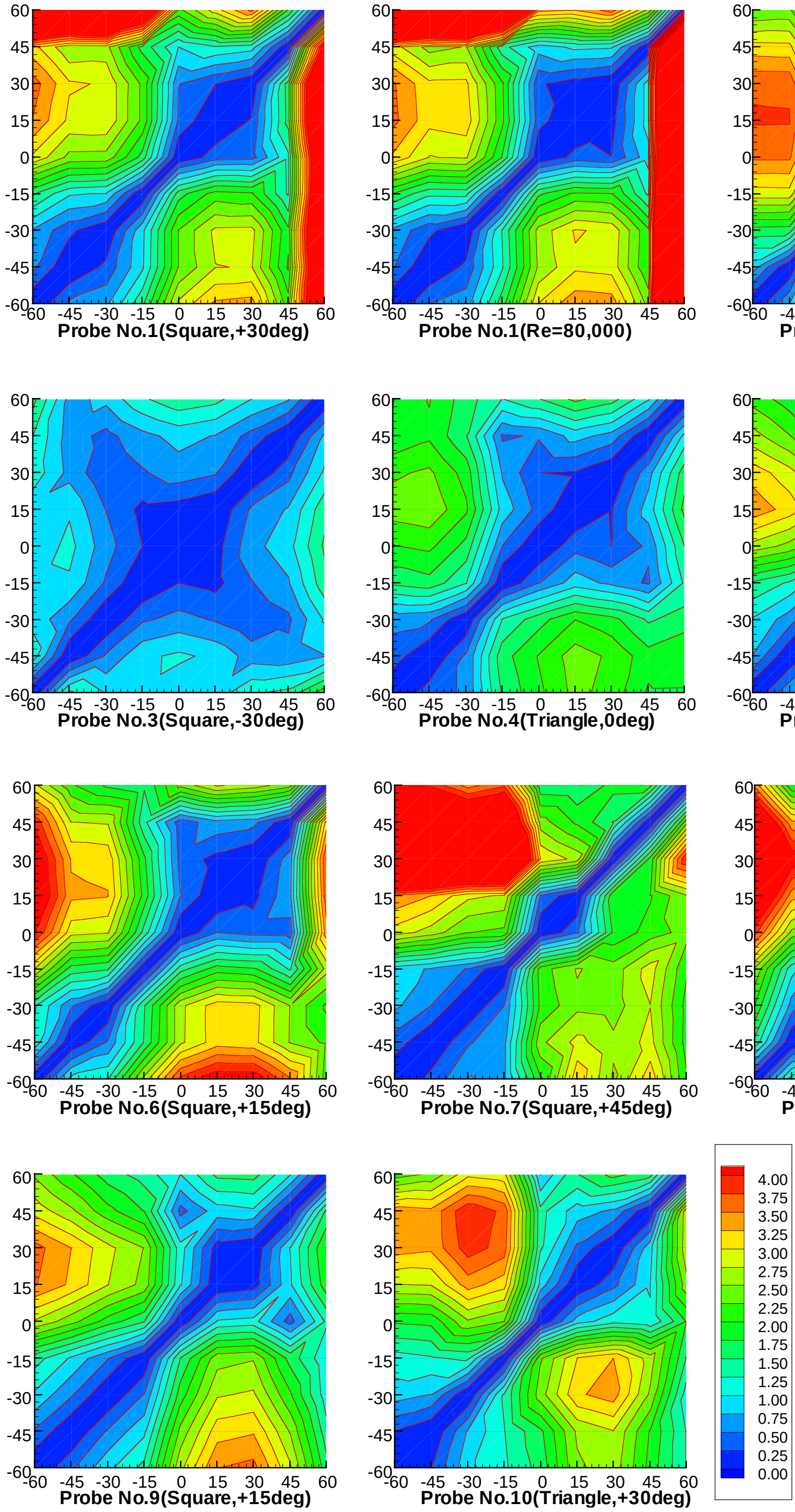
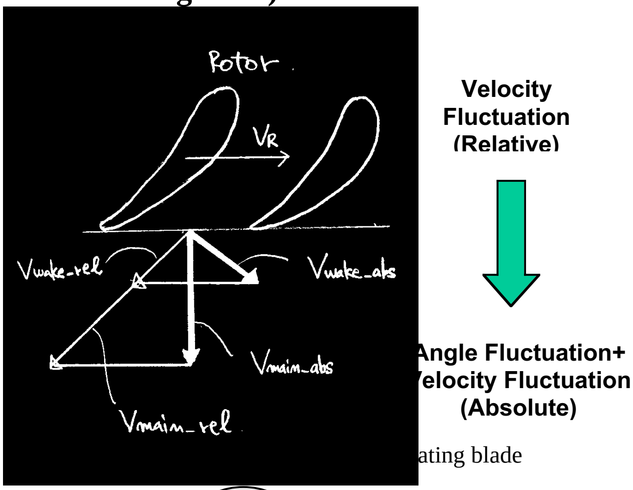



Fig.2-7 Pitch Sensitivity
(Re=40,000)

Vertical,Horizontal
Axis shows Pitch Angle

## 3.Dynamic Enlarged Model Test (Angular Fluctuating Flow)

In the flow just after rotating blades, not only the velocity but also the flow angle is fluctuating as wakes pass by. In this experiment, in order to investigate the dynamic effect of angular fluctuation flow on a probe, a probe mounted on a crank mechanism driven by a motor, oscillates at the wind tunnel exit, instead of generating fluctuating flow. Here probe No1 and No8 were selected and tested.




ating blade

**Experimental Setup**

Fig.3-2 shows the driving mechanism for the angular oscillation of the probes at the outlet of the wind tunnel. The crank mech. can generate oscillations up to a max. of 50Hz with an ampl. of 10 to 30 deg. A 16 channel Scanivalve DSA system was employed for high frequency data logging. There are 13 holes on a sensing plate which are connected to DSA with flexible tubes of about 50 mm of length. The length of tubes were designed so as to reduce the propagation delay to minimum. The propagation delay in tube was measured previously with Kulite and it was 0.0023 sec. DSA can sample with up to 200Hz. All the data was phase-locked with respect to trigger signal from the rotationg disk of crank mech and was time-compensated in data processing. The oscillation frequency was chosen appropriately in oder to avoid a few mechanical resonance of the system which had been observed in the preliminary operational check.

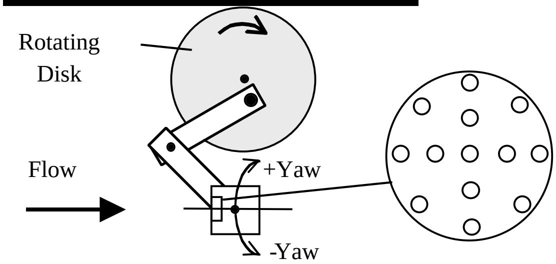



Fig. 3-2 Experimental Setup

**Experimental Condition**

In turbomachines, with the ground harmonic frequency f of the flow fluctuations being identical to the blade-passing frequency domain, free stream velocities $u_\infty$ ranging from 100 to 300m/s, the governing non dimensional parameter, Strouhal Number, for dynamic flows is of the order

$$St = \frac{fd}{u_\infty} = 0.01...0.12$$

The maximum frequency of the driving motor is 50Hz. And the minimum wind velocity is 10m/s from the view point of the accuracy of pressure transducer. Thus the maximum Strouhal Number is set at 0.15 in the experiment. Actually, a big hysteresis has been observed at relatively small Strouhal Numbers. So the condition here was sufficient to observe the dynamic effects.

| | |
|---|---|
| Probes Tested | No2, No8 |
| St =k= f * D/V = | 0.025 _ 0.150 |
| Oscillation yaw angle (Amplitude) | 20deg |
| Pitch Angle | 0 |

| | Probe No2 | | | Probe No8 | |
|---|---|---|---|---|---|
| Case | (a) | (b) | (c) | (d) | (e) |
| Velocity(m/s) | 20 | 15 | 20 | 20 | 15 |
| Frequency(Hz) | 16.7 | 12.5 | 33.5 | 16.7 | 25 |
| St | 0.025 | 0.025 | 0.05 | 0.025 | 0.05 |

**Table 3 Experimental Condition**

**Results**

Figs 3-4a to Fig.3-4e present the obtained results. They show the correlation between $C_p$ and yaw angle for one term. They are all phase-lock averaged. Not only the averaged $C_p$ of B screen hole arrangement (labelled outer holes), but also $C_p$ at centre hole are shown. The results from the static experiments are also shown. If there is no hysteresis, all the plots should coincide with static results. So the difference from static results is the hysteresis due to the dynamic effects.

As for probe No2, comparing Fig.3-4(a) with Fig.3-4(c), the hysteresis become larger with respect to Strouhal Number. The same thing is observed in probe No8. (Fig.3-4(d), Fig.3-4(e)) Comparing Fig.3-4(a) with Fig.3-4(b), they are quite similar to each other even if their fluctuation frequency are different. This is saying that the main parameter of dynamic effect is Strouhal Number in angular fluctuating flow field.

As for the dependency of hysteresis on probe shape, cylindrical probe has less hysteresis than square probe. (Fig.3-4(a), Fig.3-4(d)) This is because the separation point of cylindrical probe does not move even if the probe rotates.(= Separation point is fixed at a certain point in the absolute space.)

On the other hand, the separation point of square probe is moving as the probe rotates around it because the edge corner of the square is always the starting point of separation. If the separation point moves, the pressure potential field around a probe considerably changes and differs far away from that of static condition. Hence the sensing plate on probe is affected by the dynamic phenomena of separation. This tendency becomes larger as the Strouhal Number increases. Within the range of the experiment, it is concluded that a cylindrical type tends to be less affected by dynamic effects than a square type. Thus the best probe is cylindrical type because it is less affected by dynamic phenomena. Finally, it is concluded that the best probe is probe No.8 through both static and dynamic experiments.

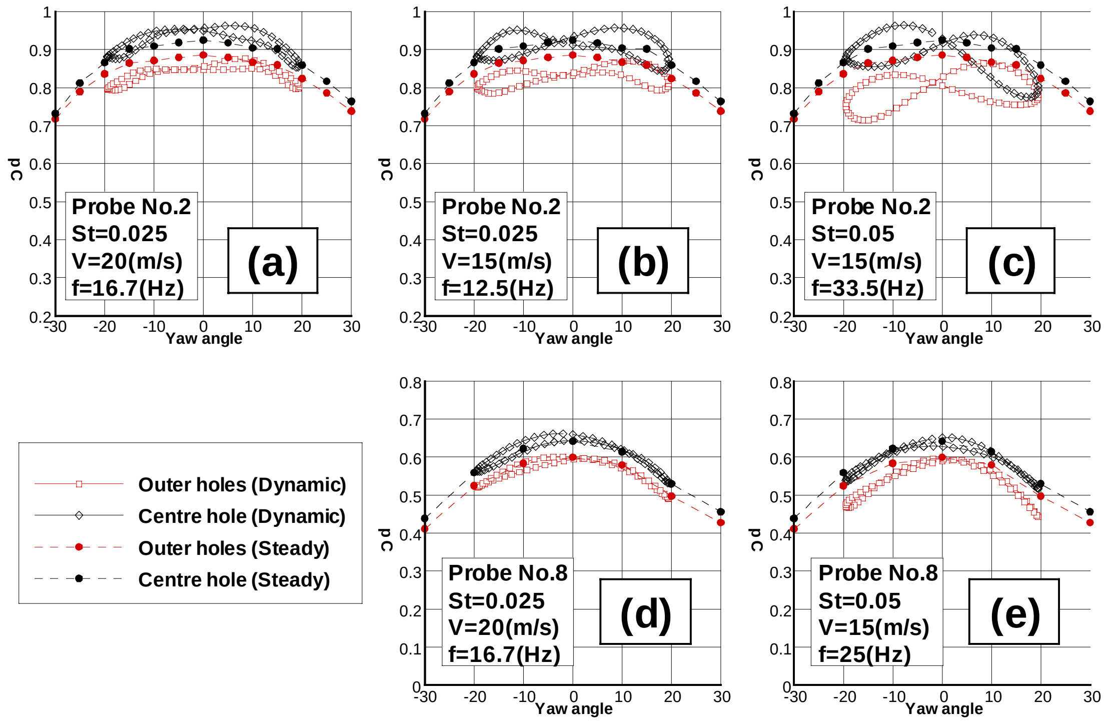



Fig.3-4 Correlation between $C_p$ and yaw angle in one term of oscillation

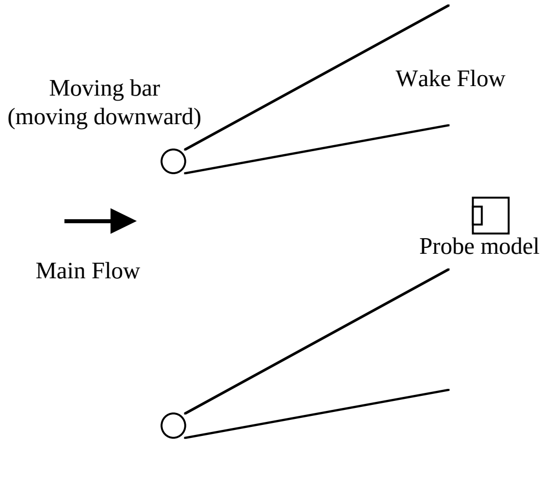
## 4. Application of enlarged probe models and the least squares method for unsteady flow measurement

In this session, a moving bar rig was employed as a wake generator by which the velocity fluctuates in both angle and magnitude. Selected probe models were employed to measure the unsteady flow behind the passing bars. The least squares method was applied for the data processing of the acquired data with enlarged model. Thus the feasibility of selected probe models for the measurement of unsteady flow field were tested. Also the accuracy and feasibility of the least squares method for data processing are discussed.

**Experimental Setup**

Fig.4-1 shows the general view of the moving bar rig. A probe model is mounted at the outlet of the wind tunnel. The rotating bars can generates unsteady wakes of up to 15Hz. In turbomachines, the width of trailing edge of a blade is comparative order of magnitude to the real miniature probe which size is expected to be less than 2mm. The enlarged models tested are 30mm in size. Accordingly, moving bars with the diameter of 20mm were used in the experiment.

A DSA system was used here again for high frequency data logging. Each bar generates trigger signal when it passes through a certain point with respect to a probe model. All the data was phase-locked in the data processing. Prior to enlarged models, hot-wire survey of the unsteady flow field was conducted. A hot-wire, which was much smaller than the enlarged probe models, was placed perpendicular to the flow and at 233mm away from moving bar. Thus the velocity fluctuation was measured beforehand.




Flow behind moving bars

Outlook of moving bar rig

Fig.4-1 Moving bar rig

**<u>Experimental Condition</u>**

A large hysteresis was observed in angular fluctuation flow at relatively low Strouhal Number around 0.025. Here Strouhal Number was set at about 0.025 aiming to generate some dynamic effects. Two conditions were selected at different passing frequency. (Table4-1, Fig.4-2)

| | | CASE 1 | CASE 2 |
|---|---|---|---|
| Probe Size | (m) | 0.03 | 0.03 |
| $V_{main}$ | (m/s) | 20.4 | 10.2 |
| Bar Passing Freq | Hz | 14.5 | 8.5 |
| Strouhal Number | | 0.021 | 0.025 |
| Probe No. Tested | | No.1,No.2,No.8 | |

**Table4-1 Experimental Condition**

**<u>Results and Discussion</u>**

Comparison of results between probe models and hot-wire is shown in Fig.4-4. All the data were phase-locked with respect to moving bar. Here the least squares method was applied for calculating unknown parameters. For all types of probes, case 2 is closer to hot-wire results than case 1. Comparing the results of velocity between hot-wire and probe model, they matches better at lower velocity than higher velocity although Strouhal number is almost the same. There are some reasons for this.

**(1) Inertial effect**

Refer to the paper as Kovasznay et.al(1968). They have shown the inertial effects at the most upstream point of a sphere can be described as follows

$$P = P_o + \underbrace{\frac{1}{2}\rho u^2}_{\text{Dynamic Head Term}} + \underbrace{\frac{3}{8}\rho a \frac{dV}{dt}}_{\text{Inertial Term}} \qquad \text{( a : Diameter of a sphere )}$$

This equation is for a sphere and cannot be applied for the probe models tested here. However the importance is that the equation is saying that the inertial effects would not be negligible when 'dV/dt' or probe size 'a' is large. Because the free stream velocity V is larger in Case1 than in Case2, the velocity deficit is more drastic and the term "dV/dt" becomes larger. This is also apparent in comparison of hot-wire results of each case.

**(2) Effects of the probe size ( length scale of unsteadiness )**

According to the results from hot-wire measurements, the wake width is larger in case2 than in case 1. (Fig.4-3) V* is non-dimensional velocity normalized by the averaged velocity of main stream. T* is also non-dimensional time normalized by time-scale of one term. The actual time for a probe to be subjected to the wake is more than it is. The ratio r is shown as follows.

$$r = \frac{w_{wk} + d}{w_{wk}}$$

As wake width becomes small, this effect becomes larger. Due to this, the calculated velocity and the other parameters show wider range in time than the velocity from hot-wire measurement of which size is much smaller than a probe. So, the length scale of a probe to unsteadiness such as wake width, plays an important role for the accuracy of the measurement. Therefore the probe size is important for the quality of unsteady measurement not only for smaller Strouhal Number but also for smaller length scale of a probe to unsteadiness such as wake width.

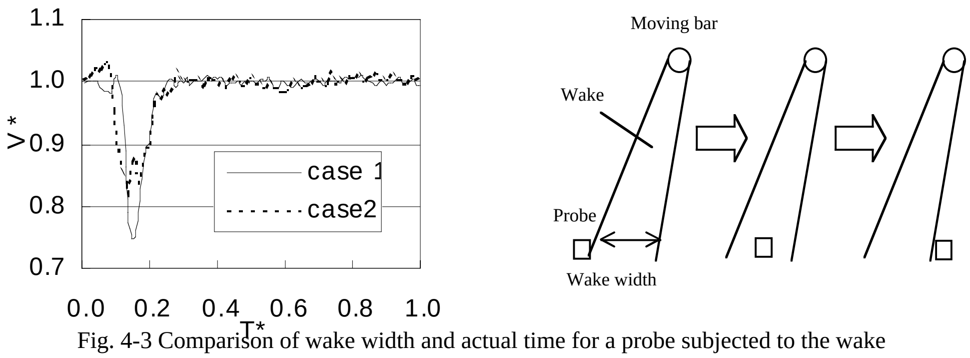



Fig. 4-3 Comparison of wake width and actual time for a probe subjected to the wake

**(3) Effects of the accuracy of $C_p$ in the calibration**

Case1 is more affected by the accuracy of $C_p$ than case2 because its dynamic head is larger. The error of $C_p$, that is the effects of calibration accuracy, is more extended as dynamic head increases. If there are any errors in calibration data, its effect is larger on case1 than case2.

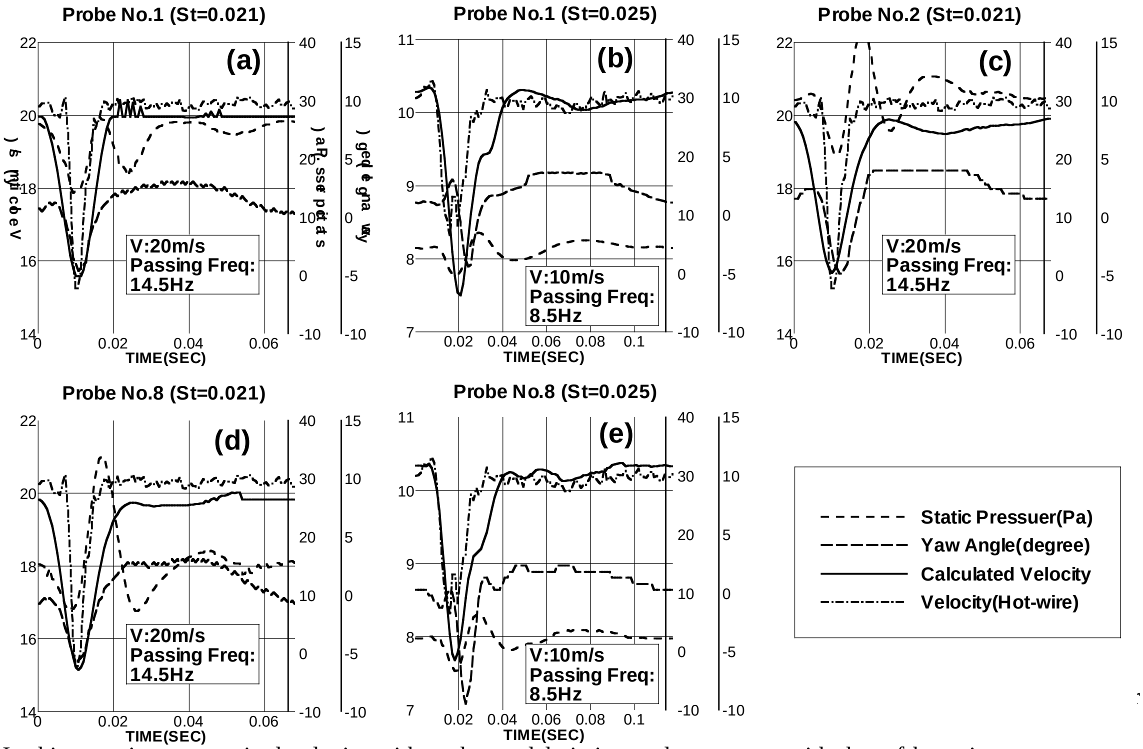



Fig.4-4 Comparison of results between Pressure Probe and Hot-wire ( phase-locked, 1 term time scale)

In this experiment, acquired velocity with probe models is in good agreement with that of hot-wire measurement. Thus the least squares method for data processing was successfully applied for unsteady flow measurement behind moving bar and its feasibility was confirmed.

## 5. Conclusion

Ten types of probe were designed and tested in a wind tunnel in order to investigate the correlation of the shape of a probe to its yaw and pitch sensitivity. Through a static enlarged model test, it was found that slanted face probe tip design increased pitch sensitivity for a single sensor pressure probe. A dynamic test was conducted for a few types of probe selected through static test. In the angular fluctuating flow, large hysteresis was observed for square type probes at relatively low Strouhal Number. It was found that cylindrical probe design tends to be less affected than square probe within the range of flow condition tested. In another dynamic test behind moving bar, where the flow is fluctuating mainly in magnitude, there is no difference observed among probe models tested. Finally the least squares method of data processing for a single sensor pressure probe model was successfully applied for unsteady flow measurement.

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