PNEUMATIC AVERAGING ERRORS OF MULTI-HOLE PROBES IN UNSTEADY FLOW

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ABSTRACT

Steady multi-hole pressure probes are used as standard practice across turbomachinery research applications. These probes have many advantages, being easy to miniaturize, simple to operate and calibrate. However there are situations when these probes can produce large errors. For example, previous work has highlighted errors due to mean-flow gradients and finite probe dimensions. However, little work has examined how these probes pneumatically average typical unsteady flows.

Through a combination of thought experiments and experimental examples, this paper demonstrates the key sources of measurement error. With simple quasi-steady arguments it can be easily shown that fluctuating flow angles are the most damaging prospect for the measurement of total and static pressures. This leads to measurement error in many practical set-ups. For example, five hole probe measurements in the shedding wake of a bluff body show up to 40% over-prediction of total pressure loss. Stationary frame measurements downstream of rotor blades can also over-predict total pressure loss due to the periodic fluctuations in angle, leading to erroneous measurement of turbomachinery performance in many experimental set-ups.

The paper concludes with some practical approaches to identify and mitigate large measurement errors when using steady multi-hole sensors in unsteady flow.

INTRODUCTION

The basic principles of three-hole-probes (3HPs) and five-hole-probes (5HPs) are well established and have been described by many authors. Typically these probes are calibrated in steady, uniform jets at a range of angles, Reynolds and Mach numbers. From the resultant calibration, the flow angle, total and dynamic pressures may be reconstructed from a combination of non-dimensional pressure coefficients.

Sources of error in 5HP measurements have been examined by several authors. Dominy and Hodson (1993) focused on the Reynolds number sensitivity of 5HPs with different geometries. Grimshaw and Taylor (2016) highlighted errors in regions of flow gradients, such as wakes, and how these can be mitigated by reducing the probe size. Bennett (1976) and Bauinger et al. (2017) discussed errors due to the pneumatic averaging of pressure fluctuations in the flow. These error sources apply to both "steady" probes, where the probe head is connected to transducers via tubing of some length, as well as unsteady probes where transducers are embedded in the probe head.

Building on this previous work, this paper considers steady probes operating in unsteady flow. Simple modelling shows that fluctuations in flow angle are the most damaging source of errors. In some cases such fluctuations can induce large errors of over 40% in total pressure loss. For turbomachinery applications, this error source can be significant when stationary frame measurements are taken behind rotating blade rows.

RESULTS AND DISCUSSION

Figure 1 demonstrates the problems caused by fluctuating flow angles. Data were collected in the shedding wake of a D-shaped bluff body in an enclosed wind tunnel, at a Reynolds number of 98,500 based on the body width W and upstream conditions. Traverse data from a 5HP are compared to:

(1) Total pressure measured by traversing a Kiel-head-pitot, which is approximately insensitive to angle fluctuations over the range ±30°.
(2) Static pressure interpolated from a row of side wall tappings.

Figure 1(a) shows the total pressure loss, which the 5HP overestimates by 43% at the wake centerline. Figure 1(b) shows that the 5HP underestimates the static pressure by up to 50% of the upstream dynamic head. These errors lead to an over-estimation of velocity in the wake by around 10%, Figure 1(c).

The paper explains these discrepancies by using quasi-steady arguments to estimate the response of the probe to fluctuating flow angles. Angle coefficients are shown to be relatively insensitive, thanks to their approximately linear variation with angle of much of the range. In contrast, total and dynamic pressure are highly non-linear, which is ultimately the source of the large errors in Figure 1.

This modelling is then applied for the turbomachinery-specific application of stationary probe measurements obtained downstream of rotating blade rows. These effects help to explain, for example, the discrepancies between 5HP and Kiel-head-pitot measurements behind a High Pressure Turbine rotor observed by Bauinger et al. (2017).

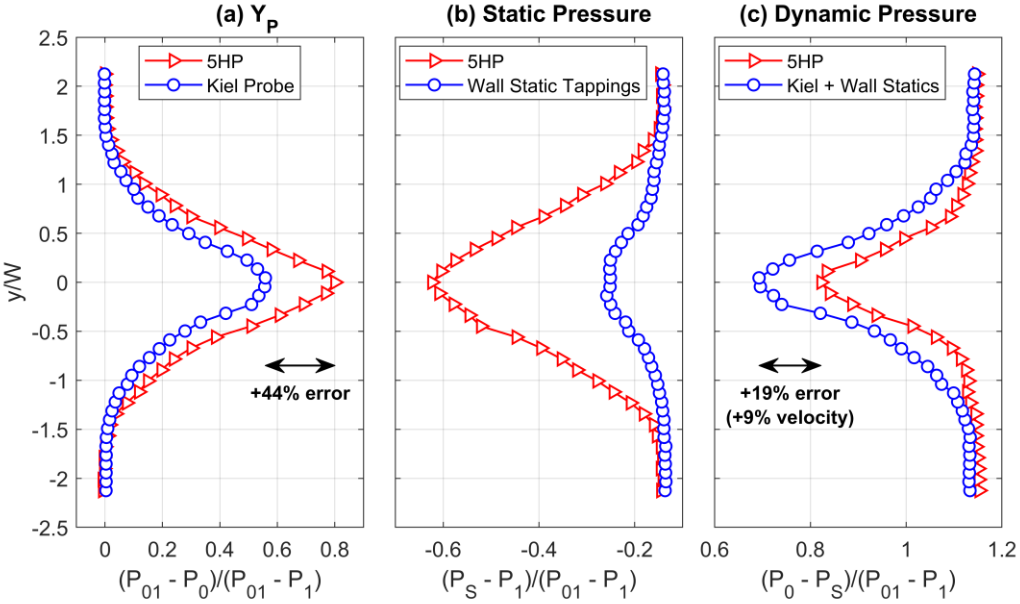

Figure 1: Total, Static and Dynamic Pressure errors from a 5HP probe in a D-shaped bluff body wake: W is the body width; measurements $4W$ downstream of the trailing edge.

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