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Improving the Fidelity of Aerodynamic Probes using Additive Manufacturing

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Biographical Details:

Ishaq Jarallah is currently a Masters student in Business at the University of Sussex. His primary interest in additive manufacturing technology stems from a private family business venture that uses similar technology. He pursued this interest by undertaking a final year degree project in this area and continues to develop the knowledge since. He believes that his current training in Business would help him further in advancing and managing the business both technologically and financially.

Vasudevan Kanjirakkad is a Lecturer in Experimental Thermo-fluid Mechanics at the School of Engineering and Informatics at the University of Sussex. He has more than 10 years of experience in the experimental field that particularly focuses on the development of efficient Gas Turbine engines for aviation and energy needs. In addition to conducing experimental research on the aerodynamic and thermodynamic aspects of gas turbines, he is also interested in the development of novel flow-instrumentation techniques that leads to accurate and consistent flow measurements.

Structured Abstract:

Purpose: This paper offers the aerodynamic testing community a new procedure for manufacturing high quality aerodynamic probes suitable for 3-D flow measurements, with consistent geometry and calibration by taking advantage of the additive manufacturing technology
Design/methodology/approach: The design methodology combines the advantages and flexibilities of CAD/CAM along with the use of Computational Fluid Dynamics (CFD) to design and analyse suitable probe shapes prior to manufacturing via Rapid Prototyping.
Findings: A viable procedure to design and possibly batch manufacture geometrically accurate pneumatic probes with consistent calibration is shown to be possible through this work. Multi Jet Modelling prototyping methods with wax based support materials is found to be a cost effective method when clean and long sub-millimetre pressure channels are to be cut.
Originality/value: Utilisation of the geometry consistency that is made possible by 3-D printing technology for the design and development of pneumatic probes is described. It is suggested that the technique could lead to batch production of identical probes thus avoiding, precious time of a skilled labourer and elaborate individual calibration requirement

Keywords: Rapid Prototyping, Pneumatic Probe, Calibration, Probe-head

Article Classification: Technical Paper

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1 Introduction

Aerodynamic testing is fundamental to the advancement of energy and transport technology (Aircraft Engines, Gas and Wind Turbines, wing and body shapes of vehicles; aircrafts, ships, cars etc.) and wind tunnel testing forms an important aspect of this. Aerodynamic pressure (or pneumatic) probes used in wind tunnel testing for measuring flow velocities and pressures are traditionally hand-made and consist of finely drilled holes or orifices at the probe-head for sensing the local pressure which are connected pneumatically with a pressure transducer using thin flexible tubing. The output from the pressure sensors are then used to deduce flow information through a careful calibration technique. The probe-head (or nose) may take different geometries/shapes based on the type of flow field that is to be investigated and the type of information that is required to be gathered. Probes can be assembled into grids or rakes in order to track the flow in the downstream areas (i.e. to measure unknown flow quantities such as pressure, flow velocity magnitude, directions etc.) from aerodynamic bodies of interest placed in a wind tunnel. Quite often they are attached to an area traversing system driven by DC stepper motors so that the probe-head surveys an area (or plane of interest) made up of discrete points. The size of the probe-head (probe volume) is important in determining the spatial accuracy of the measurement; smaller probe volumes are desired for improved spatial accuracy (as a rule of thumb, the probe-head cannot resolve flow features smaller than itself). This means that the required intricacies have to be built into a small sized probe-head volume traditionally of the order of 1 to 5 mm depending on the overall size of the test area and the size of the fluid phenomena under investigation.

Hand-manufacturing of pressure probes require a range of materials, crafting techniques and tools to satisfactorily produce particular geometries. Probe-heads with intricate shapes may typically be manufactured from softer, ductile materials like brass or nickel. However, probes exposed to harsher fluid-flow environments require greater structural strength and are therefore likely to be constructed from steel/alloys. The traditional construction of such probes is a lengthy process and requires a skilled technician to be employed. These hand-made probes are rarely flawless as there are many possibilities for inaccuracies and they often require multiple trials before an acceptable geometry is arrived at. Inaccuracies typically occur when drilling holes or while soldering or brazing, where undetected burrs could compromise the accuracy of the deduced flow variables and the sensitivity of the probe to flow parameters. Probes constructed from a combination of materials are liable to flaws as different intrinsic rates of wear could damage the probe-nose. Chipped components, cracks and leakages can occur during forming. Other difficulties include ensuring concentricity and symmetry of the probe-head and the orifices and channels that are drilled into them. For probes that are intended to resolve 3-D flows a certain level of symmetry is essential and even small deviations can cause negative results in the form of reduced accuracy and useful measuring range.

In an attempt to minimise the difficulties and shortcomings associated with traditional hand-manufacture, one could introduce the possibility of automation. Using CAD/CAM methods, pneumatic probes could be designed and built to exact specifications. This can be followed-up with numerical analysis of the probe model (using Computational Fluid Mechanics or CFD) to assess its suitability. Subsequently, an appropriate prototyping method could be employed to manufacture the probe, thus ensuring that the desired geometry is achieved towards producing an accurate flow field measurement device.

The Rapid Prototyping (RP) technology has already been used to aid aerodynamic testing in the past; Springer (1998) tested the suitability of four different rapid prototyping technologies; fused deposition method (FDM), stereolithography (SLA), selective laser sintering (SLS) and laminated object method (LOM), for wind tunnel model testing. He concluded that such models can be successfully used for subsonic, transonic and hypersonic flow testing. SLA was used to produce compressor blade models within a linear cascade test facility by Dedoussisa et.al. (2008). They reported that time and cost could be saved with SLA while achieving similar test results as those obtained from CNC machined blade models. While the above authors used rapid prototyped models for stationery model testing, Kanjirakkad et.al. (2008) made use of SLA technology to produce a rotor blade for a low speed turbine test facility. The technique was particularly employed to produce a blade with embedded pressure channels that act as pressure lines for surface pressure and concentration measurements (Figure 1). Although the tests produced successful result for their particular application, care had to be taken to prevent deformation especially due to elongation under own weight, centrifugal effects and exposure to UV component of light in the long term. More recently authors such as Kroll and Artzi (2011) have used the technique (FDM, SLA and SLS) to produce wind tunnel models of UAV aircraft shapes for teaching and educational purposes. This study demonstrated that the technology is ideal for use in student projects where prototypes are to be manufactured and tested at the very end of a design project in a time-bound and cost effective manner. The work carried out by all the authors as cited above successfully used the rapid prototyping technology to produce aerodynamic models that are to be tested in a wind tunnel environment. However the current work takes the application to the next level of fidelity where the manufacture of the test instrumentation (and not the model to be tested) itself is attempted using the rapid prototyping technology. For achieving high spatial resolution the heads of the pneumatic probes have to be much smaller (typically two or three orders of magnitude) than the models to be tested in the wind tunnel. Accuracy and repeatability of the geometry manufacture is very important as the calibration response of the probe is extremely sensitive to its shape. Consequently the geometric intricacies of the probe-head make it an ideal candidate to be rapid prototyped straight from a CAD design. The project objectives here are to design, test and manufacture a five-holed pressure probe which can be accurately prototyped for ready use. The calibration curves of a candidate probe-head geometry design as obtained from the computational fluid dynamics work at the design stage will be compared with that obtained from its 3-D printed prototype using experiments conducted in a wind tunnel.

2 Probe Design

Various types of pressure probes have been in use to aid aerodynamic testing and a very detailed account of the types of probes and the theory behind their use for various applications are explained by Bryer and Pankhurst (1971). As described by the above authors, a verity of probe shapes and sizes could be employed depending on the type of use and the number of flow parameters to be resolved at any one time. Wall static pressures could be measured using simple ‘wall tappings’ connected to a pressure sensor whereas a ‘pitot-static’ arrangement is used to resolve both the static and dynamic component of pressure at any given point in the flow. However, it has to be ensured that the pitot-static probe is facing towards the direction of the mean flow (this may not be known a priory in many real flows) for this method to work and any deviation in flow direction would reduce the accuracy of the pressure measurement. In many real flow situations associated with fluid flow applications the flow-filed is very complex and there is a need to obtain not only the pressures but also the velocity components that define the flow. Multi-holed pneumatic probes are used for measuring such flows and one of the key ability of such a probe is to resolve the flow angles along orthogonal planes, usually called the pitch-plane and the yaw plane (Figure 2). A two or three-holed probe can resolve the flow direction in a single plane (yaw), a five-holed probe is able to provide flow angles in both the yaw and the pitch planes and hence fully resolve the three dimensional flow vectors.

In order to resolve the flow quantities the probe once manufactured is placed in a wind tunnel and tested for the pressure response from its orifices. Suitable combinations of the orifice pressures are used to form what are known as the yaw coefficient (C_{yaw}) and the pitch coefficient (C_{pitch}) that characterise the sensitivity of the probe to changes in flow angles in the yaw and the pitch directions respectively. A typical five-hole probe calibration plot showing the relationship between the two coefficients is shown in Figure 3a. Although the axes are not shown for brevity, the X-axis represents C_{yaw} and the Y-axis represents C_{pitch}. Each horizontal line represents the variation in the value of the above coefficients as the yaw angle is varied from one extreme to the other (i.e. $-\psi$ to $+\psi$). Similarly each vertical line represents the represents the variation in the value of the yaw and pitch coefficients as the pitch angle is varied from one extreme to the other (i.e. $-\vartheta$ to $+\vartheta$). As seen in Figure 3a, for small yaw angles, C_{yaw} remain nominally unchanged as the pitch angle is varied from one extreme to the other. Similarly, C_{pitch} remains largely unchanged when yaw angle is varied at lower values of pitch angle. But as the angles increase the variation in coefficients become non-linear as indicated by the curved lines. Note that for a well-made symmetric probe this map would look very symmetric as shown in Figure 3a. Any geometrical asymmetry in the yaw direction including the positioning of the holes 1 and 2 (as seen in Figure 2b) would cause an asymmetry in the calibration map as shown in Figure 3b. Similarly a geometric or hole formation asymmetry in pitch direction (hole numbers 3 and 4 in Figure 2b) would cause a deformation of the map as shown in Figure 3c. Figure 3d shows the calibration map for a probe with a very small range-sensitivity as the probe-head geometry does not allow large angle flows to be resolved.

The non-dimensional nature of the coefficients plotted in the calibration map is later utilised when testing in an unknown flow field; the corresponding coefficients from the new test are then used in an inverse manner to deduce the new velocities and pressures. A calibration map generally gives a good indication of the symmetry of the probe, the range of angles at which it is most effective, and the sensitivity of the probe to changes in angle.

2.1Geometrical Design

A five-holed pneumatic probe was chosen as the candidate for this study as it is one of the most commonly used instrumentation for resolving steady 3-D flows. When properly manufactured and calibrated, such a probe is capable of providing the aerodynamicist with all three velocity vectors and the total/static pressures at any given point in the flow. A five-holed probe is symmetric with two sets of pressure tappings, vertical and horizontal, either side of the central hole. Figure 2 shows the head of a typical conical-nosed probe and the hole numbering conventions.

A full-scale CAD model was constructed to replicate the probe geometry, thus making it simpler to transfer to CAM and the CFD meshing software. The probe was specifically designed to include easy assembly of components and to limit human contribution. Figure 4 shows the inner details of the probe, orifices and the assembly of a candidate five-hole probe geometry of the conical-nose type with a half angle of 45°. The probe-head is shown to be attached at the rear to an outer tube with a 90° elbow. The outer tube contains smaller individual tubes that connect to each of the channels in the probe-head that lead to the five orifices. The rear part of the probe-head is gradually widened out so that the inner channels from the orifices could be spaced out for strength (additional material thickness) and easy connection to the hypodermic tubes that lead to the pressure sensors. The hypodermic tubes are merely inserted and glued into the corresponding channels at the back end of the probe-head. The probe-head cross section as shown here is along the pitch plane. Since the design is symmetric, the probe-head cross section in the yaw plane would be identical to this with the yaw orifice channels placed on either side of the central orifice channel.

2.2Numerical Analysis

To investigate the probe performance, the probe-head geometry is analysed using a commercial CFD tool. The probe and the control-volume representing the flow domain are discretised using a meshing application. The meshed domain (Figure 5a) is then solved for steady flow using a Navier-Stokes solver, where, boundary conditions are set to replicate the practical testing using a wind tunnel. Only the region close to the probe tip is simulated as the size of the pressure sensing region (effectively the channel opening) is too small to be affected by any static pressure field that results from the geometry of the downstream attachments as seen in Figure 4.The mesh refinement determines the accuracy of computation and hence a mesh independence analysis was conducted to ensure that the mesh is adequately refined at relevant areas and is therefore independent of the solution. Figure 5b shows the surface mesh refinement over the probe-head with clearly refined orifices and pressure channels. To simulate the pitch and yaw angle changes in a calibration experiment, the free-stream velocity is broken into three trigonometric vector components and entered into the solver. The programme is set to run at an appropriate fidelity solving the different angle combinations in the yaw and pitch planes; 0°, ±10°, ±20°, ±30°. Upon convergence, the pressure values corresponding to each of the five probe orifices are extracted, non-dimensionalised and plotted to form the calibration curves. If the calibration is acceptable, the probe design is considered for manufacture and testing.

Numerical streamlines from the CFD analysis plotted around the nose and body of the probe-heads are shown in Figure 5c. The streamlines inside the channels are not shown as they are regions of zero velocity. Faster fluid flow regions appear as red and slower fluid flow regions appear as blue. Note that the incoming flow in the case shown here is aligned with the axis of the cylindrical probe-head and therefore corresponds to a yaw angle and pitch angle of 0°. The flow accelerates as it bends around the 45° apex. The relatively sharp corner around the conical nose fixes the point of flow-separation as the flow direction veers-off from the cylinder axis. This reduces the angle range for useful operation. However, a fixed flow separation point (i.e. the sharp corner) around the conical-nose makes it more consistent and reliable.

Calibration curves for the five-hole probe are formed (Figure 6) from the pressure solution obtained from the CFD analysis. The map is nearly symmetric with the largest value of pitch coefficient reading marginally higher than the corresponding yaw coefficient. Although this may mean that the probe is likely go out of range along the pitch sense first, for the range of flow angles tested here (±30°) the calibration map is very acceptable.

3 Manufacturing Process

As described in the introduction to the paper, the most commonly used rapid prototyping methods for producing wind tunnel models are FDM, SLA, and SLS. SLA is found to produce models with a good surface finish (3-4 μm) that could be considered aerodynamically ‘smooth’ compared to FDM and SLS which typically offer surface finishes of the order of 16 μm.

After comparing a range of CAM techniques, it was decided to use 3-D printing with Multi-Jet Modelling (MJM) for manufacturing the prototype of the probe-head. MJM is an additive manufacturing method introduced by 3D Systems. In particular, the model *ProJet 3500 HD Max* has been used for the probe components used in the current work. Multiple jets are used to inject a combination of a photo-curable material (usually a liquefied plastic) and wax to lay fine layers as thin as 16 microns onto an otherwise empty tray. Wax is only used as support material or to fill the voids, unless the model itself is intended for investment casting in which case the whole model is made out of wax (with no UV curing required). A software programme is then used to slice-up the CAD file of the model into such layers and is then sent to the printer. The printer then sprays out the material through multiple jets to physically form the layers and UV light is flashed to solidify the layer thus gradually building the probe-head geometry layer-by-layer. The photo-curable material used is the *VisiJet M3 Crystal* supplied by 3D Systems due to its toughness and translucent appearance. The wax support material used was *VisiJet S300*, also from 3D Systems. Figure 7 shows a schematic of the MJM modelling process. Note that in the present case the probe-head layout used was such that the pressure channels are oriented horizontally and parallel to the plane of the build table.

Post-production, the wax based support material is dissolved with basic heat treatment, thereby eliminating the need for hand cleaning and any other material removal processes which may distort the geometry. Note that the internal pressure channels were filled with wax during the build process. Therefore such a method is particularly attractive for the five-hole probe since the individual measurement holes (and the channels) have to be small enough (0.3 mm diameter in the current designs) in order to reduce the size of the measurement volume. Similarly, no finishing or polishing is carried out, leaving the probe-nose untouched from any tooling. Beyond the objective of establishing a ‘pneumatic continuity’, the level of roundness achieved within the channels is deemed to be immaterial for the present application since there is no net flow though the channels (i.e. they merely transfer the pressure from the probe end to the transducer end). The MJM was selected for its speed and accuracy at which parts can be produced, while still remaining cost-effective. Figure 8 shows the 3-D printed probe-head part using the ProJet 3500 HD Max printer. The internal pressure channels that were previously described in Figure 4 are clearly visible here.

4 Assembly and Testing

Once manufacturing of the probe-head as shown in Figure 8 has been successfully completed, pre-cut thin-walled steel tubing (hypodermic tube) is used to extend the inner pressure channels from each of the five orifices to lead to the pressure transducer device. The steel tubes are simply inserted into the recesses on the rear side of the probe-head and are bonded to the plastic using a quick-setting glue. The larger outer tubing with an elbow shape sheathes the five inner hypodermic tubes. After assembly, the probe is tested for potential leaks. Each of the inner hypodermic tube is connected to a pressure transducer linked to a computer. Slightly larger adapters also made of hypodermic material could be used to connect to the plumbing on the transducer device as shown in Figure 9a. The probe assembly is attached to a traversing arrangement that induces pitch and yaw angle components to the incoming flow and is placed at the exit of a free-jet wind tunnel that supplies air at a prescribed speed (Figure 9b).

5 Test Results

Figure 10 shows the calibration coefficient plot for the five-hole probe as obtained from the wind tunnel experiment and that from the original numerical study of the design. The upper and lower range of the calibration coefficients match very well with those obtained from the numerical simulation. The experimental data is found to have less symmetry than intended. However details such as the marginally higher values of the limiting pitch coefficient as predicted by the design CFD is remarkably accurate. The confidence in predicting the coefficient values suggest that the asymmetry is a result minor deviation in the probe-head/nose geometry while manufacturing using the MJM method. As explained earlier using Figure 3 the asymmetry as seen in the experimentally obtained calibration map seems to result from a geometry malformation along the yaw direction. It needs to be brought to light at this point that the surface accuracy provided by the Projet 3500 printer is only 32 μm along the build tray plane and 16 μm in the plane perpendicular to it. This can still be considered to be aerodynamically rough and hence susceptible to flow behaviour that is inconsistent around the periphery of the probe-head, thus affecting the local flow pressure and the value of the resulting pitch and yaw coefficients. Despite the lack of symmetry, the probe manufactured here is still capable of accurate measurements when used in an aerodynamic model measurement scenario where the flow vectors to be measured are within the range ±30°. The result is however extremely promising and vindicates the methodology that was set out in the objectives of this study. It has been shown here that a practical aerodynamic probe with all its intricacies could be designed from scratch using a CAD tool, analysed for usefulness in a CFD study and prototyped using an appropriate rapid prototyping machine. This completely eliminates the requirement of hours of labour and the trial and error method that is employed by a skilled tool maker as is conventional.

6 Conclusions and future possibilities

Traditionally, pneumatics probes are hand-made by a skilful toolmaker in a trial-and-error manner. Upon experimental testing, asymmetries and inaccuracies of the probe geometry so produced could often render it unusable for the intended task. Obtaining a probe geometry that produces a good and acceptable calibration is thus purely a matter of chance (often needing several trials; time and resources). No two probes produced in this manner are identical and hence they are required to be calibrated individually. Today’s CAD/CAM technology offers the possibility to design and manufacture intricate geometries such as those encountered in a five-hole pneumatic probe. Furthermore, CFD can be used to numerically test the conceptual probe designs produced in CAD, prior to their manufacture, to ascertain their suitability and acceptability for a given task. It is shown through the current work that a standard procedure to produce aerodynamic probe geometries using a combination of CAD, numerical analysis and 3-D printing can be successfully devised. This can, potentially save precious time, fully eliminate the requirement for skilled labour, whilst ensuring accuracy and repeatability of manufacture. A single calibration plot could thus be potentially used for an entire batch of probes that are printed identically. It is well possible that, in the near future, ‘e-libraries’ or electronic data-bases can be devised to allow engineers to download CAD geometries of probes which can directly be printed in a rapid prototyping machine. Advances in techniques such as Metal Laser Sintering could be used to build probes that can withstand harsher test conditions. Rapid design and batch manufacture of accurate pneumatic probes could save aerodynamics researchers and test engineers valuable time, money and resources while developing and testing cutting-edge aerodynamics applications.

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Figure 1 SLA Rotor Blade with built-in surface pressure channels (Kanjirakkad, 2005)

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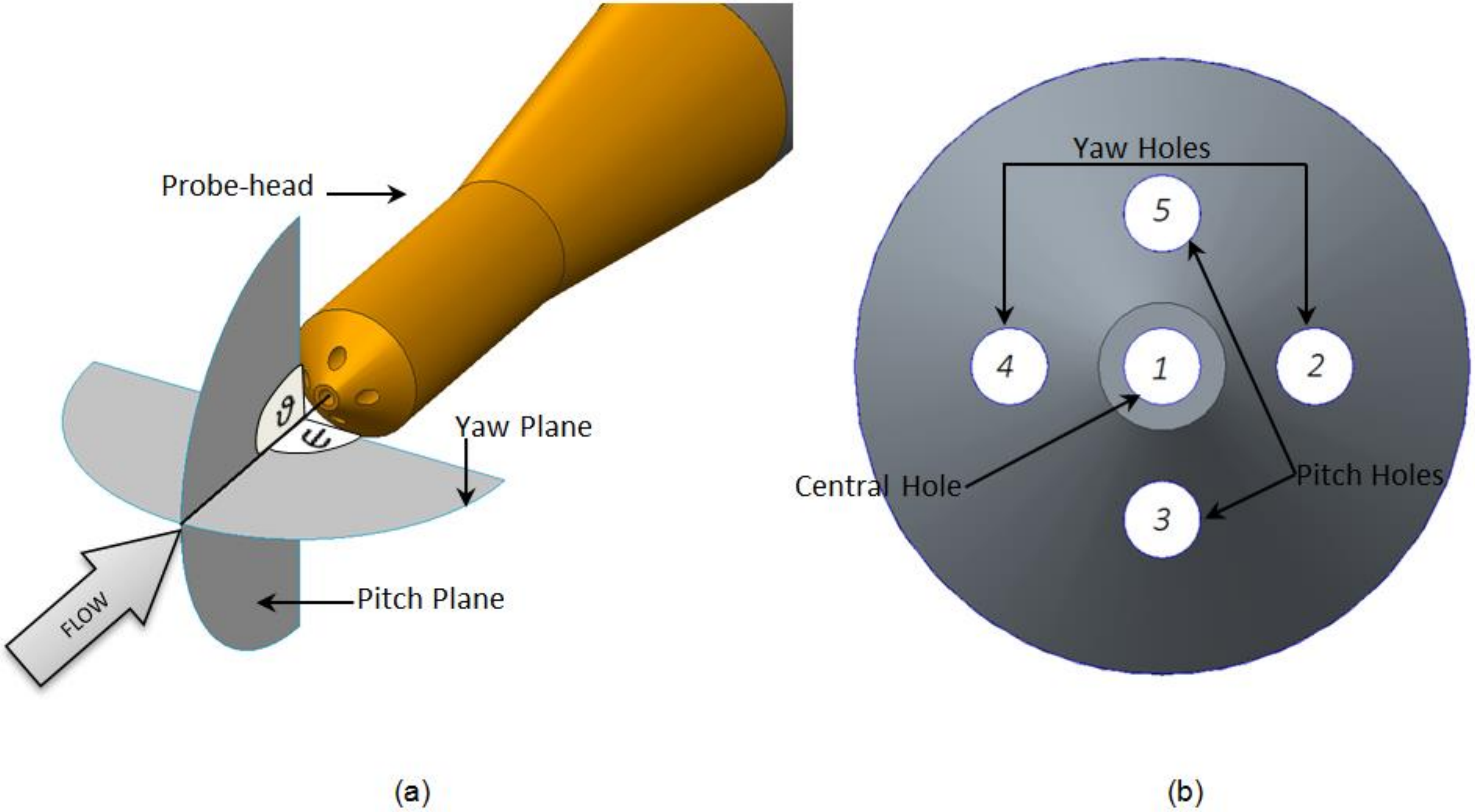

Figure 2 Five-hole probe is able to resolve flow angles (ψ,θ) in both the yaw plane and the pitch plane (a) probe head geometry (b) Probe head hole naming and numbering

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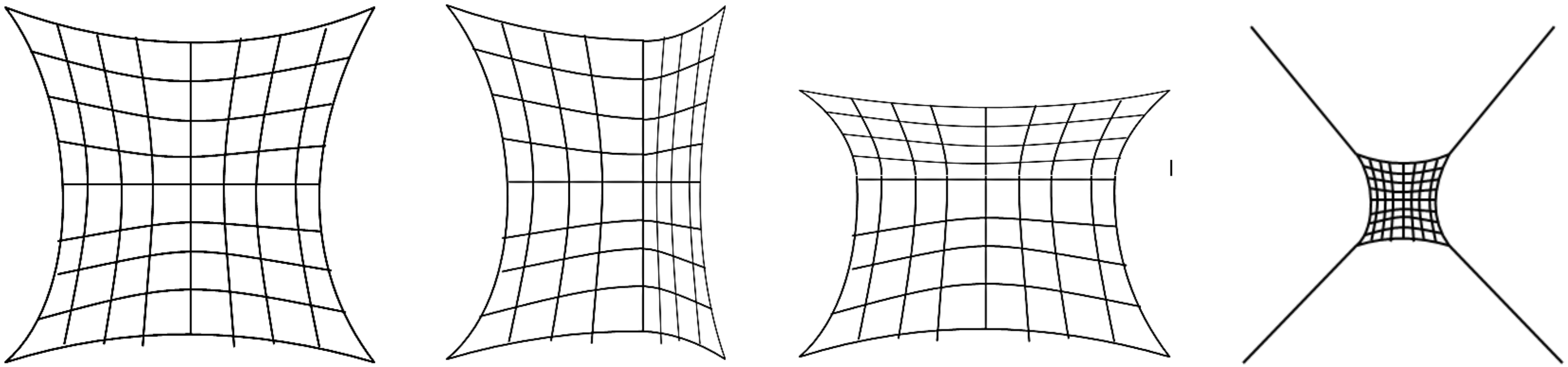

(a) (b) (c) (d)

Figure 3 Calibration plot examples for a five-hole probe

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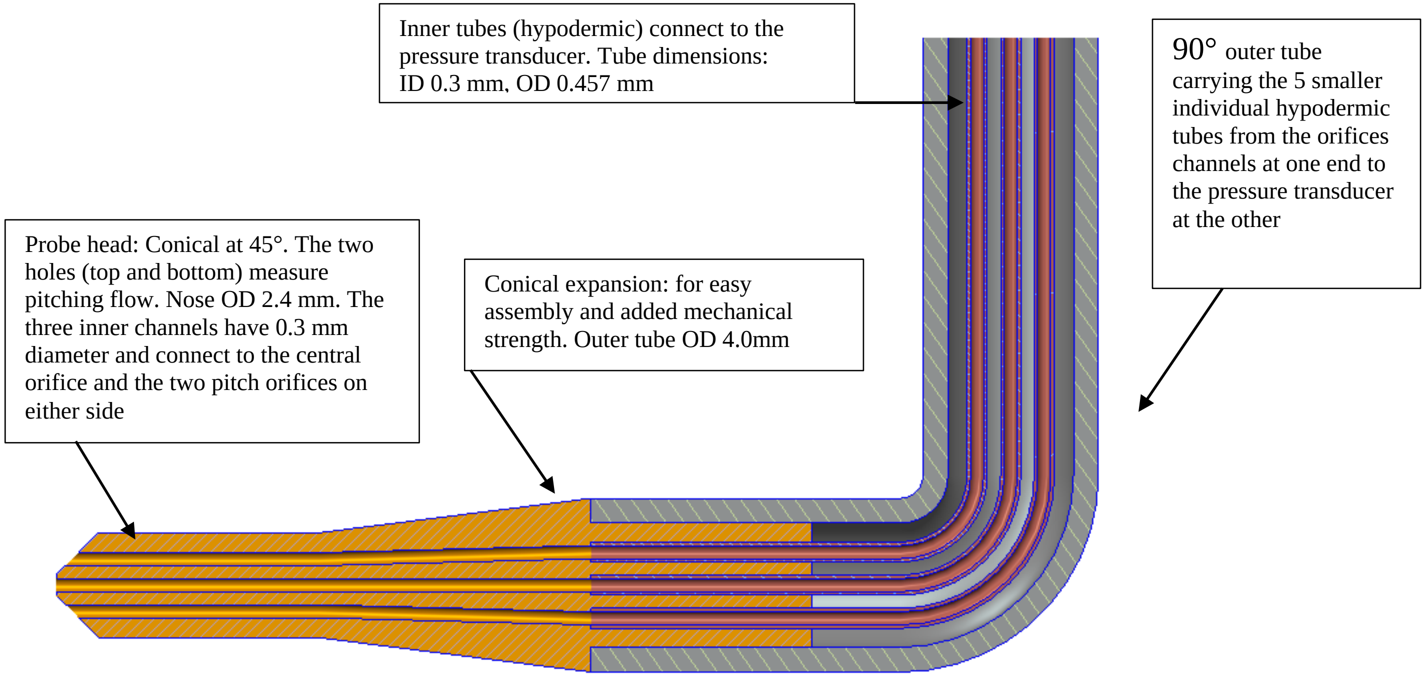

Inner tubes (hypodermic) connect to the pressure transducer. Tube dimensions: ID 0.3 mm, OD 0.457 mm

90° outer tube carrying the 5 smaller individual hypodermic tubes from the orifices channels at one end to the pressure transducer at the other

Probe head: Conical at 45°. The two holes (top and bottom) measure pitching flow. Nose OD 2.4 mm. The three inner channels have 0.3 mm diameter and connect to the central orifice and the two pitch orifices on either side

Conical expansion: for easy assembly and added mechanical strength. Outer tube OD 4.0mm

Figure 4 CAD cross section of the Five-hole probe design showing the various details

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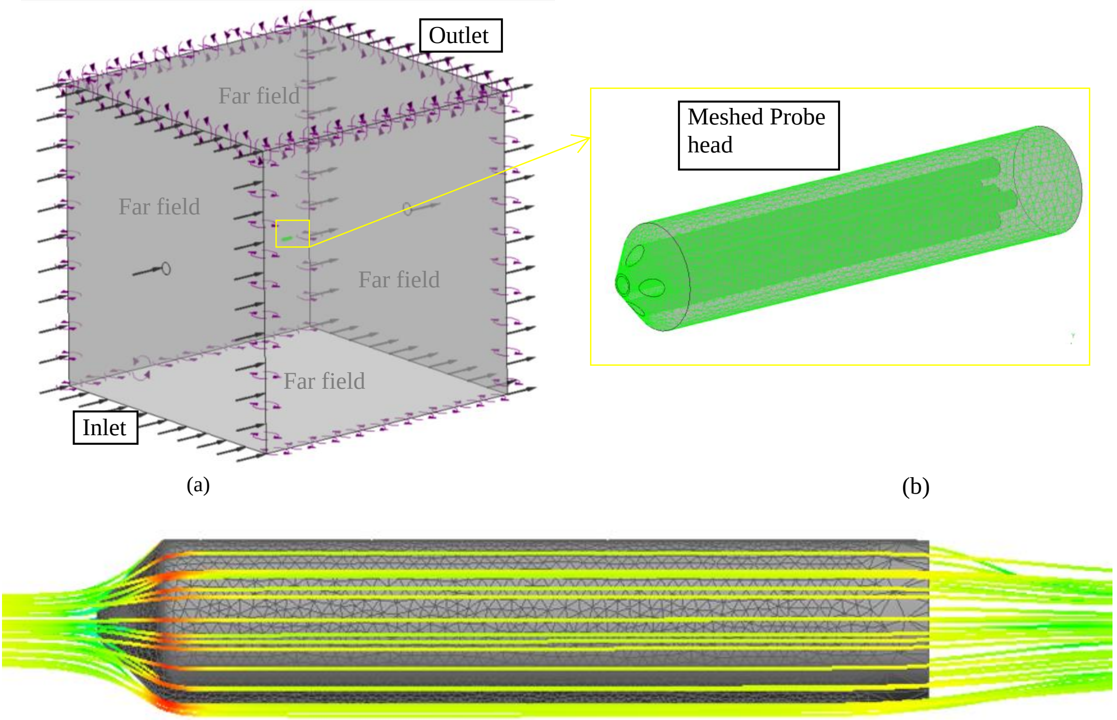

(a)

(b)

(c)

Figure 5 (a) Numerical analysis domain with the probe at the centre, (b)Details of the meshed probe head geometry, (c)Streamlines around the probe head as obtained from the numerical analysis. Streamlines coloured by velocity; showing the acceleration of the flow around the conical face of the probe

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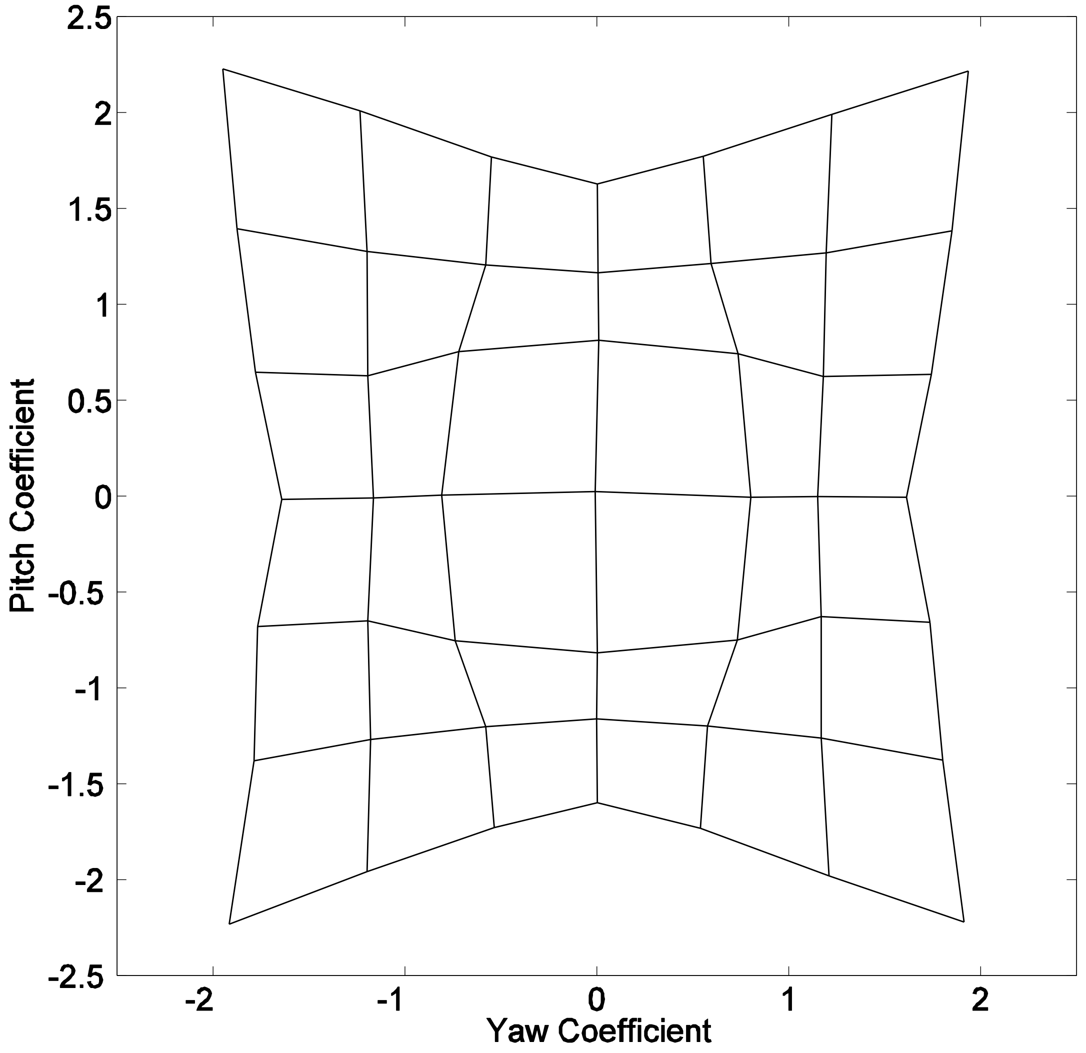

Figure 6 Calibration plot as obtained from the numerical study

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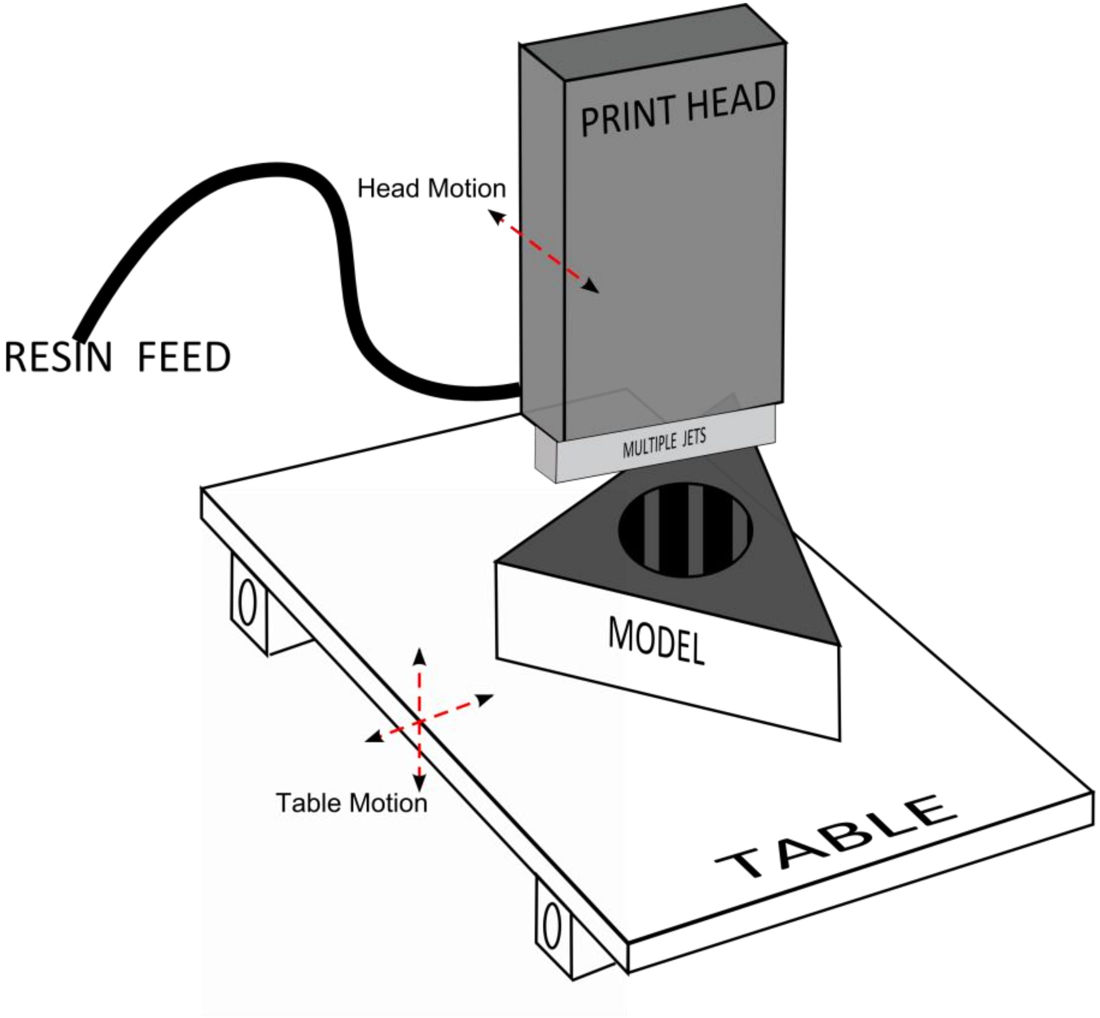

Figure 7 A schematic of the Multi Jet printing layout

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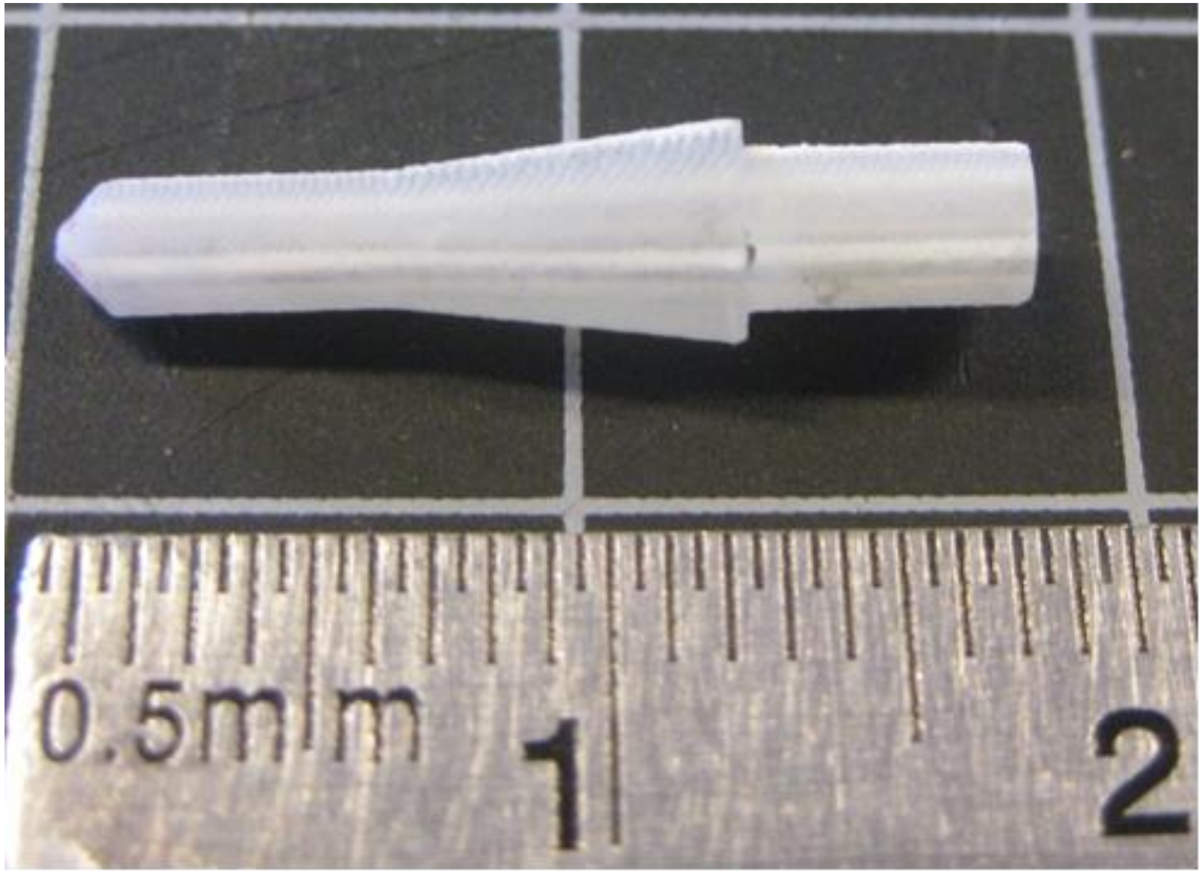

Figure 8 The probe head manufactured using Multi Jet technology

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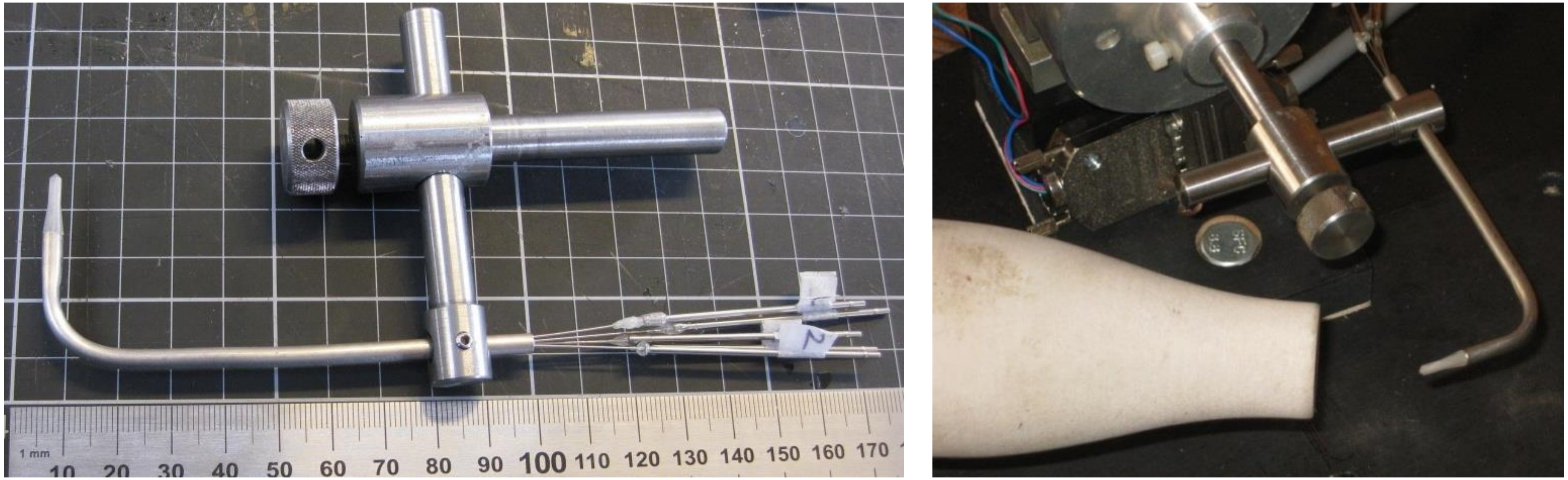

(a) (b)

Figure 9 (a) Complete probe assembly (b) Probe attached to a traverse system placed front of the flow nozzle

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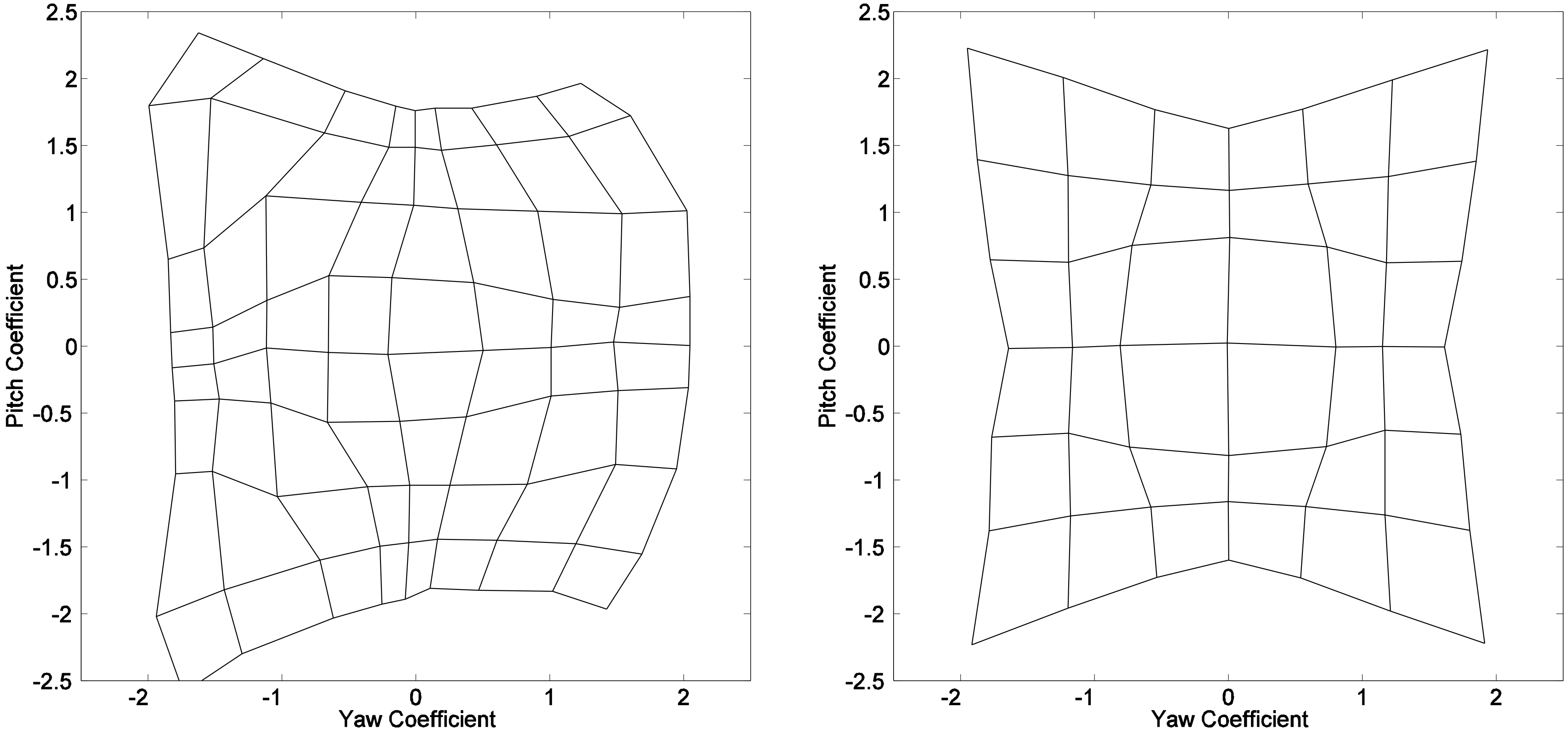

(a)

(b)

Figure 10 Calibration map of the five-hole probe design: (a) Wind tunnel experiment (b) CFD simulation

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