HIGH FREQUENCY FIVE HOLE PROBE FOR HIGH TEMPERATURE APPLICATIONS

Guillermo Paniagua, David Gonzalez Cuadrado, Valeria Andreoli, James Braun
Petal Solutions LLC, 47906 West Lafayette, USA
Lakshya Bhatnagar, Zhe Liu
Purdue University, 47906 West Lafayette, USA

ABSTRACT

Traditionally, five-hole probes suffer from resonance frequencies due to the intrusion of the probe with the flow field, this resonance depends on an array of variables such as the arrangement of the cavity sensors, dimensions of probe and head, etc [1].

This paper proposes a novel design methodology of a cooled miniature five-hole directional pressure probe able to measure at frequencies up to 100 kHz in high speed and high temperature environments. For gas turbine applications, frequencies up to 100 kHz need to be achieved [2]. The dimensions were selected to minimize the interference with the flow field [3]. With 3D Reynolds Averaged Navier Stokes simulations, a virtual calibration curve is retrieved, and the shape of the stem is optimized to reduce the effect of the unsteady vortex shedding via biomimicry [3-8]. Finally, a numerical approach is outlined to be able to cool the probe for high temperature conditions.

RESULTS AND DISCUSSION

Figure 1a depicts the frontal view of the five-hole directional probe. Five miniature Kulite sensors are embedded inside a 4 mm diameter Inconel probe. Additionally, the five recessed sensors located in the stem provide an improved performance in a wider range of Mach number, from low subsonic to transonic. The shape of the stem is inspired by the harbor seal whiskers. Figure 1b displays the location of the base pressure tapping and Fig. 1c exhibits the internal line-cavity configuration that connect the Kulites to the flow field. The internal line-cavity configuration have a diameter from 0.3 to 0.4 mm. Figure 1d shows the frequency spectrum of each recessed sensor. The simulations were carried out with three dimensional URANS simulations and solved with a second order scheme. The numerical mesh contained 7 million cells and the time-step for the simulations was 1 µs with a total computational time of 432 hrs on 20 CPU's. The vortex shedding frequency was identified around 4.4±0.5 kHz and a cylindrical stem design was compared to the whisker design. In all recessed sensors, the amplitude of the vortex shedding were reduced. Additionally, the frequency response of the acoustic waves traversing from domain inlet to outlet was identified around 2.4±0.5 kHz by the total pressure Kulite sensor ⑤.

To increase scope of applicability of the probe a cooling system is to be designed to allow the survival of the probe and installed sensors in aggressive temperature conditions that mimic closely to actual engine operational conditions. The design point used is 2000°C freestream temperature and 250°C inner surface temperature of the cavity where the Kulites are installed. A two-dimensional model of the probe cross-section was analyzed at the design conditions to determine the heat load that the cooling system will need to bear. Two strategies were considered, to use sensible cooling by making microchannels inside the probe body to circulate ethylene-glycol at sub-freezing temperatures (Fig. 2) and by using phase change materials through the same channels at higher temperature. The microchannels helps keep the size of the probe small and minimizes disturbance to the flow. The selection of the material of the probe is critical since a low thermal conductivity prevents uniform cooling of the probe body and leads to the formation of hot spots and high thermal gradients inside the probe body. Decreasing wall thickness of the probe body leads to formation of high stress positions inside the probe limiting the pressure with which the coolant is pumped inside. To simplify the design process, the channel layout is first studied in a two-dimensional projection of the probe without cavities and then checked in a three-dimensional analysis. This cooling system is then compared with a standard cooling jacket on the outside of the already manufactured probe.

Future work includes the experimental validation of the whisker design as well as an optimization to be able to reduce the effect of the vortex shedding. A methodology to obtain the flow direction from the calibration map will be introduced assessing the uncertainty in the flow direction and pressure retrieval.

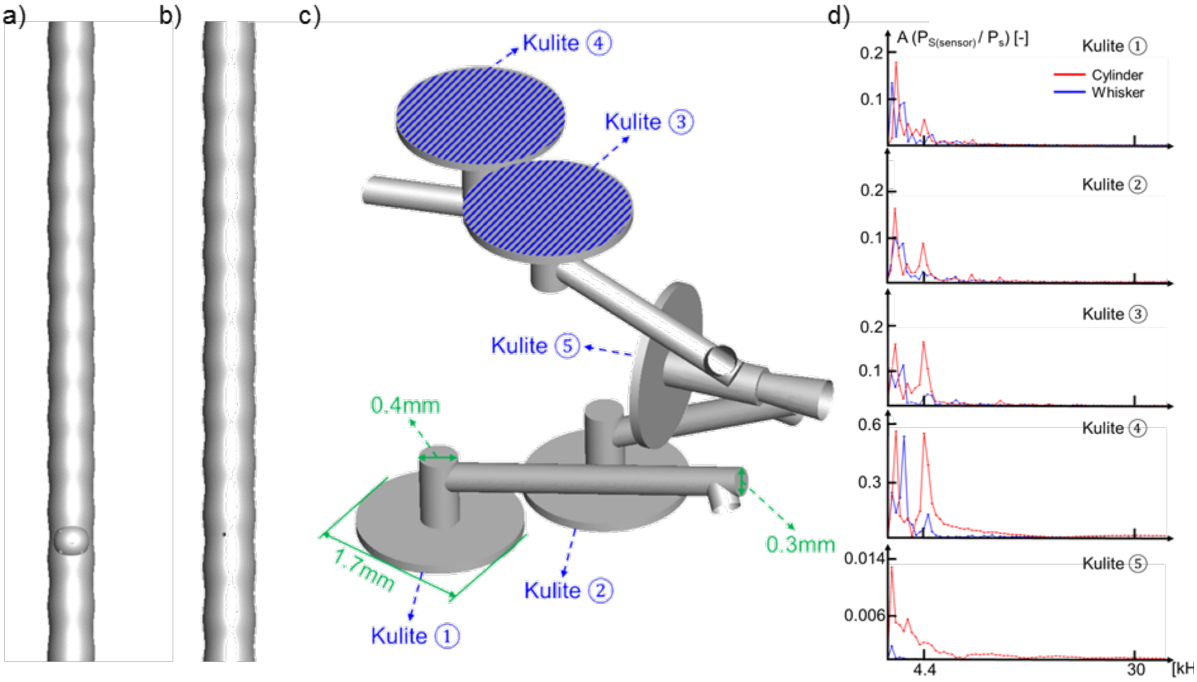

Figure 1: a) probe head, b) back of the probe, c) detail of the Kulite locations, d) Fast Fourier Transform of the five pressure sensors

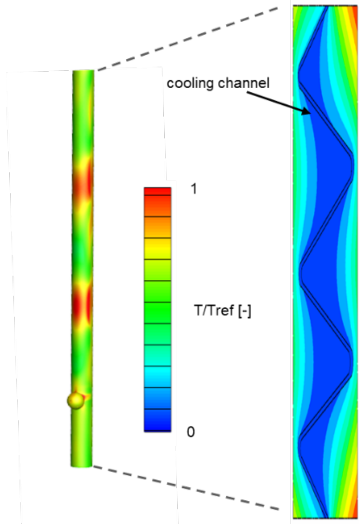

Figure 2) detail of the cooling channel

REFERENCES

[1] Paniagua, G., and Denos, R., 2002, “Digital Compensation of Pressure Sensors in the Time Domain,” Exp. Fluids, 32(4), pp. 417–424.
[2] Ainsworth, R. W., Miller, R. J., Moss, R. W., and Thorpe, S. J., 2000, “Unsteady Pressure Measurement, " Meas. Sci. Technol., 11(7), pp. 1055-1076.
[3] Liu Z, Paniagua G. Design of Directional Probes for High-Frequency Turbine Measurements. ASME. J. Eng. Gas Turbines Power. 2017;140(1):011601-011601-10. doi:10.1115/1.4037640.
[4] Beem, Heather R., and Michael S. Triantafyllou. Wake-induced ‘slaloming’ response explains exquisite sensitivity of seal whisker-like sensors. Journal of Fluid Mechanics 783 (2015): 306-322.
[5] Beem, Heather R., and Michael S. Triantafyllou. Wake-induced ‘slaloming’ response explains exquisite sensitivity of seal whisker-like sensors. Journal of Fluid Mechanics 783 (2015): 306-322.
[6] H. Beem, M. Hildner and M.S. Triantafyllou, Calibration and validation of a harbor seal whisker-inspired flow sensor, Smart Materials and Structures 22:1, 2013, 014012.
[7] P.V. Alvarado, V. Subramaniam, M. Triantafyllou, Performance analysis and characterization of bio-inspired whisker sensors for underwater applications, Proceedings of the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp.5956-5961, 3-7 Nov. 2013.
[8] H. Hans, J. Miao, M. Triantafyllou, Vortex-Induced Vibration (VIV) Reduction Properties of Seal Whisker-Like Geometries, Bulletin of the American Physical Society 58, 2013.
[9] H. Beem, et al. “Harbor Seal Vibrissa Morphology Reduces Vortex-Induced Vibrations”, American Physical Society Division of Fluid Dynamics Conference, 2011