Sujet thèse / PhD subject 2025

Titre Thèse	Multiphysics Inference System for Multiparameter High-Temperature Gradient Sensors in Turbulence Measurement and Real-Time Gas Analysis.	
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Projet phare principal		
Demande de fléchage IEMN ? (Energie / Nanocaractérisation / Technologies Neuromorphiques)	Oui ./ Non : non Flagship choisi :	
Demande de labellisation Université de Lille (GREAL, labellisée)	Oui / Non : Label :	
Financement acquis Oui ☐ Non ☑ Partiel ☐	Si acquis (total ou partiel), préciser : (contrat, organisme, Université étrangère, , ….) :	
Financement demandé	Contrat Doctoral Etablissement	ULille ☐ Centrale Lille ☑ JUNIA ☐
	Région ou Autre Préciser :	Co financement (Préciser l'origine, demande en cours, et si acquis ou pas) :
		CLI et Région HdF ; demande en cours

A. Résumé / Abstract :

Turbulence remains one of the most complex unresolved phenomena in classical physics, especially in **high Reynolds number flows** and **intricate geometries** found in industrial applications. The limitations of purely numerical methods underscore the critical need for **advanced instrumentation systems** that can provide accurate, empirical data. In this context, the development of **Wall Shear Stress (WSS) sensors** is essential for studying turbulent flows in **aeronautics** and related industries. The AIMAN group at IEMN has led groundbreaking efforts in **thermal MEMS technologies**, resulting in the innovative **High-Temperature Gradient Sensor (HTGS)**, which measures **thermal conductivity, diffusivity, temperature,** and **pressure**.

This thesis aims to advance **HTGS technology** by incorporating **silicon carbide (SiC)**, enabling operation in **harsh, high-temperature, and chemically reactive environments**. Additionally, the project will develop a modular, embedded **Acquisition and Multiphysics Inference (AIMu)** system that fully exploits the capabilities of HTGS sensors for **wind tunnel testing** and **gas analysis**. The AIMu system will incorporate **high-speed, high-resolution acquisition channels**, providing **real-time data analysis** and **AI-based inference** to autonomously monitor and control **multiphysics phenomena**.

The project will also include extensive **wind tunnel testing** in collaboration with **ONERA**, using both **low-speed** and **high-speed wind tunnels** to calibrate and validate the sensors across various flow regimes, from **subsonic** to **supersonic**. These tests will ensure the HTGS sensors are capable of accurate and reliable measurements of **wall shear stress** and **pressure**, ultimately advancing the state of the art in both **aerodynamic** and **industrial applications**.

I. Context and motivation:

The complexity of turbulence lies in the fact that it remains an **unresolved problem** in classical physics, with no obvious solution. In simplified scenarios involving basic geometries and low Reynolds number flows, analytical solutions or numerical simulations are available. However, **industrial applications** involve higher Reynolds number flows and complex geometries, where relying solely on numerical simulations is insufficient. Predicting turbulence behavior in such configurations is impossible without resorting to **empirical data** [Lö99]. Consequently, there is a crucial need for **advanced instrumentation systems** capable of resolving intricate flow dynamics.

Experimentally investigating **high Reynolds number turbulent flows** entails addressing very short **spatial** and **temporal scales**. In aeronautic applications, the scales of interest are typically 100 µm or less spatially, while temporal scales require a bandwidth of at least **10 kHz** (and up to several hundred kilohertz) [Ch05, Ka09]. The need for **space- and time-resolved metrology systems** for skin-friction measurement is particularly critical in **experimental aerodynamics**. In response to these challenges, numerous researchers have developed **MEMS-based Wall Shear Stress (WSS) sensors**, which achieve both **high spatial** and **temporal resolution** while minimizing sensor size. The primary design criterion for miniaturization is based on maintaining an l/dl/dl/d ratio exceeding 200 to comply with end-conduction restrictions. Over the past decade, three research groups have pioneered some of the most innovative **hot-wire probe designs** (cf. FIGURE 1).

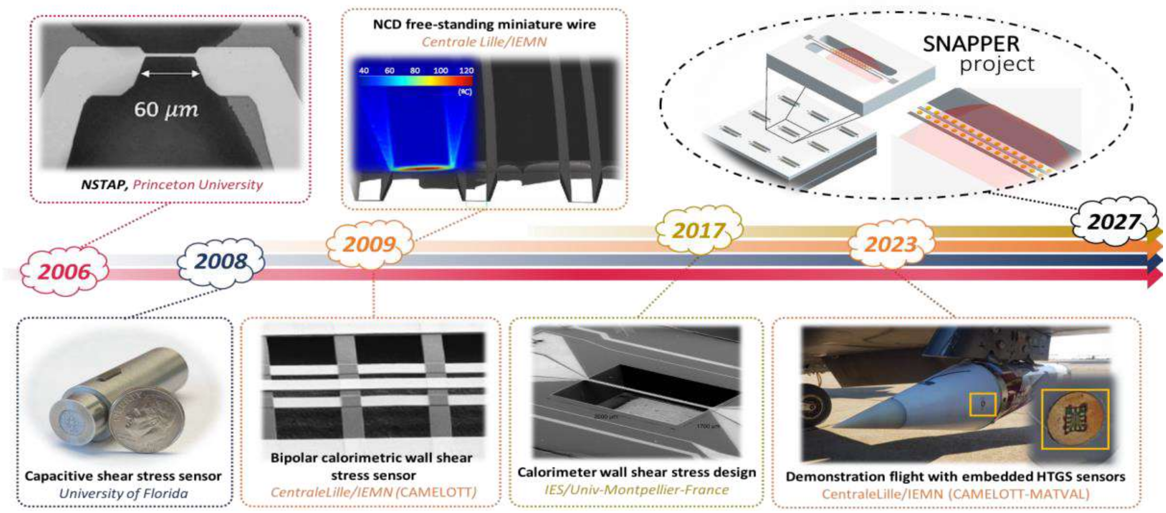

FIGURE 1 : Timeline of key research teams in WSS sensor development including the vision of SNAPPER ANR project recently accepted .

The first effort to apply **MEMS techniques** to develop a **free-standing sensor** capable of traversing a flow field was reported in 2006 [Pe11, Ta12, Ku06]. However, it was not until 2010 that Bailey et al. [Ba10] achieved sufficient calibration and validation for accurate **turbulence measurements**. In 2009, the AIMAN/IEMN group introduced the first design for **multi-parameter measurements**, encompassing **pressure** and **bipolar WSS** (both amplitude and direction) [Vi13, Ta12]. The initial **wind tunnel calibration** and validation were conducted in 2016 [Gh16b]. In 2017, IES/Univ-Montpellier-France proposed the **calorimeter WSS design** [We17]. These technologies have undergone rigorous and successful **wind tunnel testing** across various flow regimes [Ko21, Le21, Gh19, Gh20].

Over the past fifteen years, the AIMAN group at IEMN, in collaboration with **ONERA**, has developed significant expertise in **thermal MEMS technologies** for **aerodynamic flow metrology** and **closed-loop flow control**. These technologies have been extensively tested in **ONERA wind tunnels** across a range of flow configurations, from **subsonic flows** to speeds approaching **Mach 0.8** [Gh19, Gh21]. This technological progression has yielded two **patents** [Pe11, Vi13] and received financial support from the **EADS Foundation** (2006–2009), the **Innovation Defense Agency** through thesis funding, and projects such as **ASTRID** (CAMELOTT: 11/2014–05/2018) and **ASTRID-Maturation** (CAMELOTT-MATVAL: 11/2018–03/2023). The **AIMAN group** was a pioneer in revisiting **MEMS hot-wire designs**, introducing a **diamond-based structure** [Ta15] to create mechanically robust hot wires, thereby relaxing the **length-to-diameter ratio constraint** (cf. FIGURE 2).

More specifically, the team proposed and patented a **multi-parameter thermal sensor** (**HTGS: High Temperature Gradient Sensor**) capable of measuring **thermal conductivity**, **thermal diffusivity**, **temperature**, and **pressure** of the fluid. Over the past ten years, the group has focused on the design's capability for measuring both **friction magnitude** and **direction** [Vi13, Gh16a] using a **calorimeter configuration**. FIGURE 2 illustrates the overall concept of the **calorimeter**, the developed device, and the proposed package for **robust** and **flush-mounted integration**. Over the past three years, as part of **Sylvain Kern's PhD work** and the **PEPR RESIST program**, we have extended the use of these designs to **harsh environments** by incorporating **silicon carbide (SiC)** as a material. We developed innovative technological processes to utilize **SiC** as both a heating and sensing element. This advancement has paved the way for a new generation of **hot-wire sensors** capable of operating in **extreme conditions**, including **high temperatures** and **corrosive gas environments**, opening new opportunities for demanding applications.

FIGURE 2: HTGS calorimeter wall shear stress design (left). Flush mounted device with Through Silicon Vias (middle). Coaxial integration of the HTGS sensor (right).

The objective of this thesis project is to develop a **low-profile**, **fluid-compensated wall shear stress sensor** package based on **SiC technology** capable of providing both **mean** and **fluctuating shear stress data**. Additionally, the project aims to design an embedded **Acquisition and Multiphysics Inference (AIMu)** system that fully exploits **HTGS sensor technologies** for **aerodynamic wind tunnel testing** or **gas analysis applications**. This integrated system will enable **closed-loop active flow control experiments** and **online analysis of gas properties**.

To achieve this, the project leverages **AIMAN's existing calorimeter WSS sensor system** and extends its capabilities to include measurement of **pressure** and **diffusivity** of fluid. The proposed system will include **backside electrical contacts** using **AIMAN's via-hole fabrication and packaging processes** to ensure a **low-profile form factor** and a **smooth sensor surface** while significantly reducing fabrication complexity and cost. **Analog and digital electronics** will be co-located with the sensor, and **power and signal transmission** will utilize **slip rings** and/or **wireless transmission methods** to interface with a **data acquisition system**.

II. Thesis project Overview:

This thesis focuses on developing a modular, embedded Acquisition and Multiphysics Inference (AIMu) system designed to fully exploit High-Temperature Gradient Sensor (HTGS) technologies. The project includes advancing HTGS sensor technology by incorporating silicon carbide (SiC) as a core material, ensuring operational robustness in high-temperature, high-speed, and chemically reactive environments. SiC's thermoresistive properties provide reliable performance for hot-wire sensors in harsh conditions. The AIMu system targets advanced aerodynamic wind tunnel testing and industrial gas analysis, addressing the growing need for high-resolution, fluid-compensated measurement systems in challenging operational conditions.

1. Development of HTGS Sensors with SiC (collaboration avec CRHEA) :

A key aspect of this thesis is the advancement of HTGS sensor technology using SiC (silicon carbide)as the primary material. SiC's unique properties, including high thermal stability, chemical resistance, and mechanical robustness, make it ideal for:

- Measuring thermal conductivity, diffusivity, temperature, and pressure in extreme conditions.
- Operating in high-temperature, chemically reactive, or high-speed flow environments, such as wind tunnels and industrial gas processes.

This development aims to establish a new generation of SiC-based HTGS sensors for both research and industrial applications.

2. Acquisition and Multiphysics Inference (AIMu)

The AIMu system will feature high-speed, high-resolution analog acquisition channels to meet the rigorous demands of aerodynamic metrology. These channels, with a bandwidth exceeding 100 kHz and optimized gain, will handle multiphysics sensor configurations, including:

- Wall shear stress sensors (hot-wire anemometers and calorimeters).
- Pirani pressure sensors.
- Diffusivity.

The AIMu system will support advanced real-time data analysis techniques, such as Fast Fourier Transform (FFT), Wavelet analysis and Direct convolution of sensor data. AI-based inference will primarily focus on reduced data representations (e.g., FFT diagrams) but will also explore direct analysis of raw data to enable autonomous monitoring and control of multiphysics aerodynamic phenomena.

By integrating Multiphysics inference, the system will offers fluid-independent measurements, reducing the need for individual recalibrations and enabling streamlined, cost-effective sensor production.

3. Integration and Characterization of Micro-Sensors in Low- and High-Speed Wind Tunnels (Collaboration with ONERA)

The integration and characterization of micro-sensors will be carried out in collaboration with ONERA using reference sensors and controlled aerodynamic setups. This will involve both low-speed and high-speed wind tunnel experiments to assess the performance of the sensors in varying flow regimes. These experiments aim to:

- Validate the accuracy and reliability of the micro-sensors for measuring wall shear stress and pressure across various flow conditions.
- Identify and calibrate sensor responses in both subsonic and supersonic regimes.
- Establish a robust dataset for evaluating the sensor's performance in realistic operational scenarios, supporting their integration into advanced aerodynamic and industrial applications.

This comprehensive characterization will ensure the sensors are well-suited for deployment in a wide range of fluid dynamics studies, from fundamental research to practical industrial use cases.

- Low-Speed Wind Tunnel Calibration : The micro-sensors will be integrated into a flat plate configuration and characterized alongside reference sensors in an Eiffel-type open-circuit wind tunnel. This facility features a test section measuring 300 × 300 mm² with an adjustable velocity range of 0 to 40 m/s, ideal for studying turbulent boundary layers. The experimental setup will involve: 1) Mounting the sensors on the wall of a flat plate where a canonical turbulent boundary layer develops. 2) Using the controlled flow characteristics to evaluate the sensors' response to wall shear stress and pressure with high precision. 3) Comparing the sensor's output against reference measurements for calibration purposes.

- High-Speed Wind Tunnel Testing : To progressively increase the complexity of the studied flows, the micro-sensors will also be tested in two high-speed wind tunnel configurations at ONERA Lille, allowing access to compressible flow regimes across different Mach numbers: 1) Open-Circuit Wind Tunnel capable of generating compressible flows with Mach numbers ranging from 0.5 to 0.8. This facility will be used to evaluate the sensor's performance in moderate compressibility conditions. 2) Closed-Circuit Wind Tunnel designed to produce highly compressible flows at Mach 1.4. This setup will simulate more extreme aerodynamic conditions, enabling the characterization of sensor responses at supersonic speeds.

III. Références :

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IV Compléments

Ce projet s'inscrit parfaitement dans les thématiques de l'I-SITE ULNE, notamment le Hub **"Monde numérique au service de l'humain"** via le développement de capteurs MEMS disruptifs, et **"Science pour une planète en mutation"**, avec des applications centrées sur l'aérodynamisme et la mobilité durable. Il répond à un besoin sociétal majeur : l'industrie du transport, face à des enjeux économiques et environnementaux, cherche à réduire ses consommations énergétiques et ses impacts écologiques, notamment les émissions et nuisances. Le **contrôle des écoulements aérodynamiques**, rendu possible par des capteurs et actionneurs de pointe, constitue une solution clé pour atteindre ces objectifs. Au-delà de l'aéronautique, la technologie de capteur proposée a des implications larges dans de nombreux domaines, y compris la **détection des gaz**. Avec l'évolution de l'industrie chimique, les gaz inflammables, explosifs, et toxiques sont de plus en plus présents dans notre quotidien. Cela génère une demande importante pour des **capteurs de gaz fiables**, compacts, abordables et énergétiquement efficaces, avec des applications dans des secteurs tels que les processus industriels, la pharmacie, le stockage des aliments, la surveillance environnementale, la sécurité nationale et la santé. Le caractère **multi-paramètres** du design proposé permet la détection de gaz simples voire le mélange de gaz, et le temps de réponse de ce capteur permettra également d'adresser la **cinétique** dans les réacteurs.

Le projet s'appuie sur des **compétences solides** au sein de l'équipe, déjà active depuis plusieurs années dans le domaine du contrôle des écoulements. L'exploitation de nouveaux matériaux et microstructures vise à relever les **défis technologiques** associés à cette thématique.

Le projet s'inscrit pleinement dans les initiatives régionales stratégiques, notamment dans le cadre du **CPER RITMEA 2021-2027**, relatif aux transports, en collaboration avec un consortium régional regroupant **LAMIH**, **LMPKF**, **INRIA**, **ONERA** et **IEMN**. Il contribue également aux travaux de la fédération de recherche **TTM** et de la plateforme **CONTRAERO** dans le cadre du CPER **ELSAT 2020**, axées sur le contrôle des écoulements et la métrologie de la turbulence. Par ailleurs, ce projet se positionne au cœur du **flagship IoT** de l'IEMN, ainsi que dans le cadre du **CPER IMETECH**, renforçant ainsi son alignement avec les priorités régionales en matière de recherche et d'innovation.

Concernant le **co-financeur**, Centrale Lille, le projet participe à renforcer son positionnement stratégique en matière de **recherche d'excellence**, en lien avec ses priorités sur les **transports intelligents**, l'**énergie propre** et la **transition énergétique**. Il s'inscrit dans des enjeux majeurs tels que les transports et la mobilité durable, la **micro-nano-science** et le **contrôle des écoulements turbulents**.

Le projet bénéficie également d'une forte **valorisation au niveau national et international**. Il s'intègre dans les programmes prioritaires de l'**Equipex Nanofutur** et du **PEPR Electronique** (projet RESIST), visant à dynamiser l'industrie électronique à l'échelle nationale et européenne, et à contribuer à la recherche sur les micro-capteurs.