Colloquium Final Report
N.659 – Metamaterials in fluid flows and beyond

Dates and location: **25/03/2025 - 28/03/2025, Groningen, The Netherlands**
Chairperson **Anastasiia O. Krushynska**
Co-Chairpersons **Francesco Avallone (Italy), Marios Kotsonis (The Netherlands), Muamer Kadic (France)**

Conference fees

Regular registration fee **550.0 €**
Reduced (one-two days) and accompanying person registration fee **400.0 €**
PhD students and start-up companies' registration fee **300.0 €**

What other funding was obtained?

We have received financial support from

- **the Engineering and Technology Institute Groningen, Faculty of Science and Engineering, University of Groningen, The Netherlands, based on an application submitted by A.O. Krushynska.**
- **the "MetaFlow" project (KICH1.ST04.22.010) funded by the Dutch Research Council (NWO)**

What were the participants offered?

The registration fees included:
- the electronic book of abstracts;
- a colloquium dinner on March 27th 2025;
- daily coffee breaks and three lunches;
- a welcome reception and social activity on March 25th 2025.

Due to the economic crisis in the U.S. and visa issues in China, some participants were unable to attend the event. This resulted in fewer participants than confirmations.

The EUROMECH membership fee was paid separately, directly through the EUROMECH website. Therefore, the member and non-member participants are listed together.

Participants

1. Woutijn Baars
2. Federico Bosia
3. Jacopo Maria De Ponti
4. Andrei Faragau
5. Isabella Fumarola
6. Pavel Galich
7. Michael Haberman
8. Thomas Hunter

9. Marios Kotsonis
10. Ivana Kovacic
11. Joo Hwan Oh
12. Antonio Palermo
13. Bart Van Damme
14. Gregg Abate
15. Francesco Avallone
16. Caleb Barnes
17. Nicolas Benard
18. Sidharth Beniwal
19. Gareth Bennett
20. Andrea Bergamini
21. Claire Bourquard
22. Alessandro Casaburo
23. Pierre Champeaux
24. Yi Chen
25. Johan Christensen
26. Giada Colombo
27. Régis Cottereau
28. Corentin Coulais
29. Marie Couliou
30. Richard Craster
31. Steven Cummer
32. Elke Deckers
33. Nicolo Fabbiane
34. Nicholas Fang
35. Ningyuan Fu
36. Antonio Gliozzi
37. Jacopo Grassi
38. Jean-Philippe Groby
39. Xueying Guan
40. Abdelrahman Hisham Ahmed Sabri Hassanein
41. Quentin Hopman
42. Mahmoud Hussein
43. Wontae Hwang
44. Umberto Iemma
45. Solkeun Jee
46. Abigail Juhl
47. Taehoon Kim
48. Minkyung Kim
49. Lukas Kleine-Wächter
50. Julian Koellermeier
51. Mohammad Kojourimanesh
52. Ajay Kottapalli
53. Anastasiia Oleksandrivna Krushynska
54. Vincent Laude
55. Olivier Marquet
56. Kathryn Matlack
57. Albert Medina
58. Mehrshad Mehrpouya
59. Fabien Méry
60. Theodoros Michelis

61. Mostafa Nouh
62. Parisa Omidvar
63. Federica Ongaro
64. Miguel Onorato
65. Vincent Pagneux
66. Giuseppe Petrone
67. Lorenzo Pierpaoli
68. Bastiaan Piest
69. Kamiel Politiek
70. Jacopo Serpieri
71. Marc Serra Garcia
72. Ioannis Spanos
73. Kristof Stejivers
74. Antonios-Lykourgos Synodinos
75. Marie Touboul
76. Vincent Tournat
77. Vincent Tournat
78. Can Tumer
79. Can Tumer
80. Bogdan Ungureanu
81. Antonis Vakis
82. Martin Van Hecke
83. Laxmi Srinivas Vellala
84. Hema Chandra Venkata Megha Shyam Veluvali
85. Jiayu Wang
86. Zhuoyue Wang
87. Dea Wangsawijaya
88. Nicholas Waterson
89. Martin Wegener
90. Jieun Yang
91. Guohui Yin
92. Quan Zhang
93. Xiaoling Zhong
94. Rui Zhu

Scientific report

Metamaterials are artificially engineered materials whose effective properties arise primarily from their internal architecture rather than their chemical composition. Over the past two decades, they have transformed the way researchers approach the control of waves and fields, including electromagnetic, acoustic, elastic, and hydrodynamic phenomena. This EUROMECH colloquium was conceived as a forum to assess the current state of the art, foster cross-disciplinary exchange, and identify challenges that must be overcome to translate laboratory-scale concepts into real-world technologies.

We brought together world-leading experts from the two fields—Fluid Flow Control and Metamaterials—and provided a platform to foster collaboration and develop novel metamaterial solutions for controlling fluid flow. We will introduce the concepts of architected materials and their unprecedented properties to the Thermodynamics and Fluid Dynamics community, which is now primarily linked to Applied Mathematics and specific fields of Engineering, including Aerospace, Civil, Chemical, and Biomedical Engineering, which rarely interact with one another.

Altogether, there were 94 participants and 74 presentations & pitches. The list of participants is given above; the full program is available on the colloquium website https://euromech659.sciencesconf.org/program?lang=en. Besides, there was ample time for informal stimulating discussions among the participants during the coffee breaks, lunches, colloquium dinner, and social activity.

All the talks were formally separated into nine thematic sessions:

1. Introduction to Metamaterials and Flow
2. Metamaterials Beyond Flow
3. Noise Reduction
4. Aerodynamics and Porous Media
5. Acoustic Metabarriers and Surface Water Waves
6. Acoustic and Elastic Waves
7. Elastic Metamaterials
8. Application of Metamaterials
9. Poster Pitches and Discussions

We also had two brainstorming panels: (1) Fluid Flows and Metamaterials and (2) Metamaterials, an Industry Pitches session.

The submitted contributions reflect a strong balance between theory and practice in the two mentioned fields. Many contributions emphasize multiscale modeling strategies that combine analytical homogenization with high-fidelity numerical simulations and experimental validation. Others focus on manufacturing routes, robustness, and scalability, which are essential for industrial uptake. The colloquium also highlighted the increasing role of instabilities, nonlinearity, and tunability in metamaterial design, moving beyond static, linear paradigms toward adaptive and multifunctional systems.

1. Introduction to Metamaterials and Flow

This session focused on foundational frameworks for understanding and designing metamaterials interacting with fluid flows. Contributions in this area addressed both aeroacoustic performance and the broader implications of flow–structure coupling. Several presentations proposed general theoretical frameworks for designing acoustic metamaterials, emphasizing the role of effective boundary conditions and impedance-based descriptions. These approaches aim to bridge the gap between microscale geometrical features and macroscale flow-induced noise behavior. By combining asymptotic analysis with numerical simulations, the presentations demonstrated how carefully designed surface architectures can suppress or redirect acoustic energy generated by turbulent flows. Another key theme was the integration of flow physics into metamaterial concepts. The presented works showed that accounting for mean flow, shear layers, and turbulence is essential for realistic predictions. These contributions introduced subsequent sessions by establishing a common language and set of tools for treating metamaterials in aerodynamic environments.

2. Metamaterials Beyond Flow

The largest thematic block of the colloquium explored metamaterials in regimes extending beyond classical flow-related applications. The contributions covered mechanical, acoustic, and multiphysical metamaterials with novel functionalities. A prominent topic was the exploitation of mechanical instabilities, such as buckling and snap-through, to achieve extreme or switchable effective properties. Multi-step auxetic metamaterials, for instance, were shown to exhibit controlled deformation pathways, enabling negative Poisson's ratios over large strain ranges. These designs challenge conventional assumptions about material stability, reframing instability as a resource rather than a

limitation. Other contributions addressed programmable and reconfigurable metamaterials, where geometry and connectivity can be altered post-fabrication. Such systems enable on-demand tuning of stiffness, band gaps, and wave-guiding characteristics. The studies emphasized both design algorithms and experimental demonstrations, underscoring the feasibility of translating abstract concepts into tangible prototypes. Overall, this session highlighted a shift toward adaptive, nonlinear, multifunctional metamaterials that respond intelligently to external stimuli.

3. Noise Reduction

Noise reduction remains one of the most promising applications of acoustic metamaterials. The colloquium contributions addressed both passive and hybrid strategies for mitigating unwanted sound. Traditional porous materials were revisited through the lens of metamaterial design, with studies demonstrating how hierarchical porosity and embedded resonant elements can significantly enhance low-frequency absorption. These designs aim to overcome the thickness constraints that limit conventional absorbers. Other works focused on metasurfaces for sound absorption and reflection control. By spatially varying impedance at subwavelength scales, these metasurfaces can achieve tailored acoustic responses, including broadband absorption and directional scattering. Importantly, several contributions emphasized robustness and manufacturability, recognizing that real-world noise-control solutions must perform reliably under varying environmental conditions. The session as a whole highlighted the strong potential of metamaterials to revolutionize noise mitigation technologies.

4. Aerodynamics and Porous Media

This thematic session explored the intersection of aerodynamics, porosity, and metamaterial design. Porous media were shown to play a critical role in both aerodynamic performance and acoustic behavior. Several contributions examined flow through engineered porous structures, highlighting how pore geometry and connectivity influence pressure drop, flow stability, and noise generation. These insights are particularly relevant for applications such as aircraft liners, ventilation systems, and energy devices. Coupled aeroacoustic models were presented to predict sound generation and attenuation in porous metamaterials under realistic flow conditions. The studies underscored the importance of capturing multiscale interactions between flow turbulence and solid microstructure. Overall, this session demonstrated that porous metamaterials offer a versatile platform for simultaneously addressing aerodynamic and acoustic challenges.

5. Acoustic Metabarriers and Surface Water Waves

This session addressed the manipulation of acoustic waves and, in some cases, their coupling with surface water waves. The concept of acoustic metabarriers emerged as a recurring theme, referring to structures designed to block, redirect, or absorb sound in unconventional ways. Several studies explored guided surface acoustic modes supported by structured interfaces. By tailoring the surface geometry, the researchers demonstrated strong acoustic confinement, enabling efficient attenuation or redirection of sound. These mechanisms were shown to be particularly effective at low frequencies, where traditional acoustic treatments are often bulky or ineffective. Extensions of these ideas to surface water waves highlighted intriguing analogies between acoustics and hydrodynamics. Metastructured barriers were shown to influence wave dispersion and energy localization, suggesting potential applications in coastal protection and wave-energy management. The contributions in this session illustrated the power of cross-domain analogies and reinforced the idea that metamaterial concepts can transcend traditional disciplinary boundaries.

6. Acoustic and Elastic Waves

The control of wave propagation lies at the heart of metamaterials research, and this section brought together contributions addressing both acoustic and elastic waves in structured media. Several studies have investigated band-gap formation, mode conversion, and wave localization in periodic and quasi-periodic structures. Numerical techniques, including Bloch analysis and time-domain simulations, were employed to map dispersion relations and identify regimes of interest. Nonlinear wave phenomena also received attention, with presentations demonstrating how amplitude-dependent responses can be harnessed for wave modulation and energy harvesting. These effects open new avenues for devices that adapt dynamically to changing excitation conditions. By considering acoustic and elastic waves within a unified framework, the contributions emphasized the shared physical principles underlying diverse metamaterial systems.

7. Elastic Metamaterials

Elastic metamaterials formed a central pillar of the colloquium, with contributions spanning theoretical modeling, numerical analysis, and experimental validation. The unifying objective was the control of elastic wave propagation and structural response through architected microstructures. Several studies have investigated locally resonant elastic metamaterials, in which embedded resonators create frequency band gaps at wavelengths much larger than the unit-cell size. They demonstrated how careful tuning of resonance frequencies and coupling mechanisms can yield broadband attenuation or highly selective filtering of elastic waves. Other presentations focused on chiral and anisotropic elastic metamaterials, which exhibit direction-dependent wave propagation and non-reciprocal behavior. Such properties are particularly relevant for vibration isolation, seismic protection, and advanced sensing applications. Experimental efforts showcased additive manufacturing as a key enabler for complex elastic architectures. By combining 3D printing with in situ testing, the researchers validated theoretical predictions and assessed the influence of manufacturing tolerances on performance. Collectively, the contributions showed the maturity of elastic metamaterials as a research field with clear pathways toward engineering implementation.

8. Application of Metamaterials

The final thematic session synthesized application-oriented contributions that spanned multiple domains. These works demonstrated how metamaterial principles can be tailored to address specific engineering problems. Applications included lightweight structural components with enhanced damping, compact acoustic liners for transportation systems, and adaptive barriers for environmental noise control. In each case, the studies emphasized performance gains relative to conventional solutions. This section reinforced the message that metamaterials are transitioning from laboratory curiosities to enabling technologies with tangible societal impact.

9. Poster Pitches and Discussions

The poster session served as a forum for early-career researchers and doctoral students. A wide spectrum of topics was represented, reflecting the diversity of the participants' backgrounds. Several contributions focused on novel design methodologies, including topology optimization, inverse design, and data-driven approaches for tailoring effective properties. These works sparked discussions on the balance between computational efficiency and physical interpretability, as well as on the integration of machine learning tools with classical physics-based models. Experimental advances were another prominent theme. Posters showcased innovative fabrication techniques, including multi-material additive manufacturing, micro-structuring at sub-millimeter scales, and hybrid assembly methods that combine rigid and compliant components. Discussions emphasized practical challenges, including manufacturing tolerances, repeatability, and the scalability of laboratory prototypes toward larger systems.

Industry Pitches

Industrial participation was a key strength of the colloquium, reflecting the growing interest in metamaterials from commercial stakeholders. They focused on practical challenges, performance requirements, and pathways to market. The contributors emphasized scalability, cost, and reliability as critical factors influencing adoption. Case studies illustrated how metamaterial concepts are being integrated into products for noise control, vibration mitigation, and structural health monitoring.

This colloquium showcased the remarkable breadth and depth of contemporary metamaterials research. From fundamental theory to industrial application, the contributions revealed a field that is both scientifically rich and technologically relevant. Key trends include the embrace of nonlinearity and instability, the integration of flow and multiphysics effects, and a growing focus on manufacturability and robustness. Looking ahead, continued progress will depend on close collaboration between disciplines, advances in fabrication, and sustained engagement with industry.

Video of the EUROMECH 659 colloquium: https://youtu.be/0iurYB1ut8A?si=IXcGmaCESFzF_TC6

The topics discussed at the colloquium formed the basis for a review paper, accepted for publication in the *Nature Communications* journal on January 27, 2026:
Avallone, F., Bosia, F., Chen, Y., Colombo, G., Craster, R., De Ponti, J. M., ... & Krushynska, A. O. (2025). Metamaterials and Fluid Flows. arXiv preprint arXiv:2509.05371.

Number of participants from each country

COUNTRY	PARTICIPANTS
Netherlands	33
Italy	13
France	13
United States	9
United Kingdom	5
Korea South	5
Ireland {Republic}	3
Germany	3
China	3
Switzerland	2
Belgium	2
Spain	1
Israel	1
Serbia	1
TOTAL	**94**