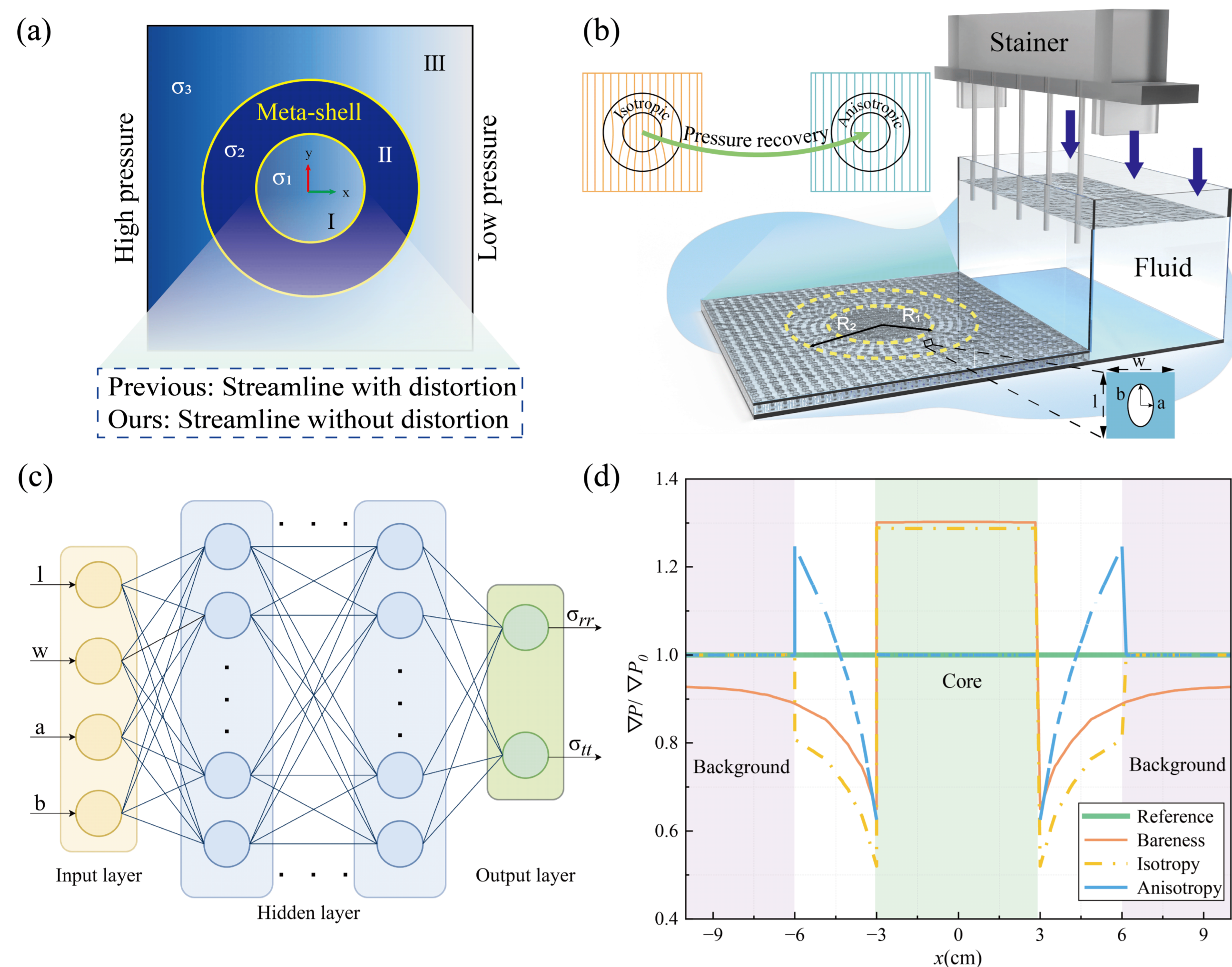


## I Introduction



**The Challenge:** Conventional flow-field sensors inherently distort the surrounding fluid due to permeability mismatch, leading to inaccurate measurements.

**The Objective:** To develop a "distortion-free" hydrodynamic sensor that achieves perfect pressure recovery in the sensing core while remaining invisible to the background flow.

**Our Solution:** A rationally designed metamaterial shell with anisotropic permeability, inversely optimized via a deep neural network.

## II Main Theory

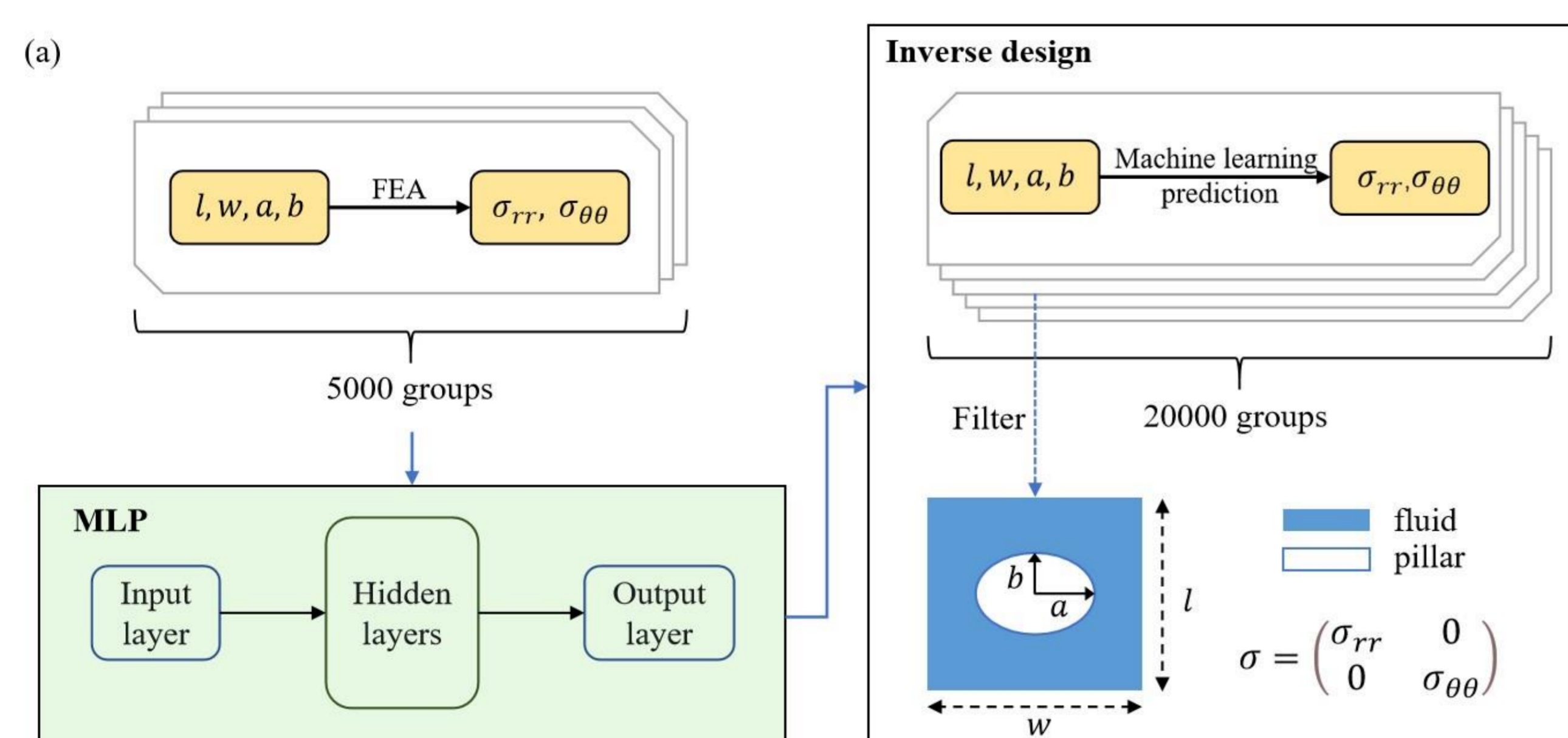
Governed by Darcy's law for low Reynolds number regimes:

$$\nabla \cdot (\sigma \nabla P) = 0$$

The system consists of three regions: **Sensing Core**, **Metashell**, and **Background**.

To achieve invisibility and high-accuracy sensing, the metashell must possess specific anisotropic permeability  $\sigma = \text{diag}(\sigma_{rr}, \sigma_{\theta\theta})$  to smoothly bridge the core and the background.

## III Machine Learning Based Inverse Design

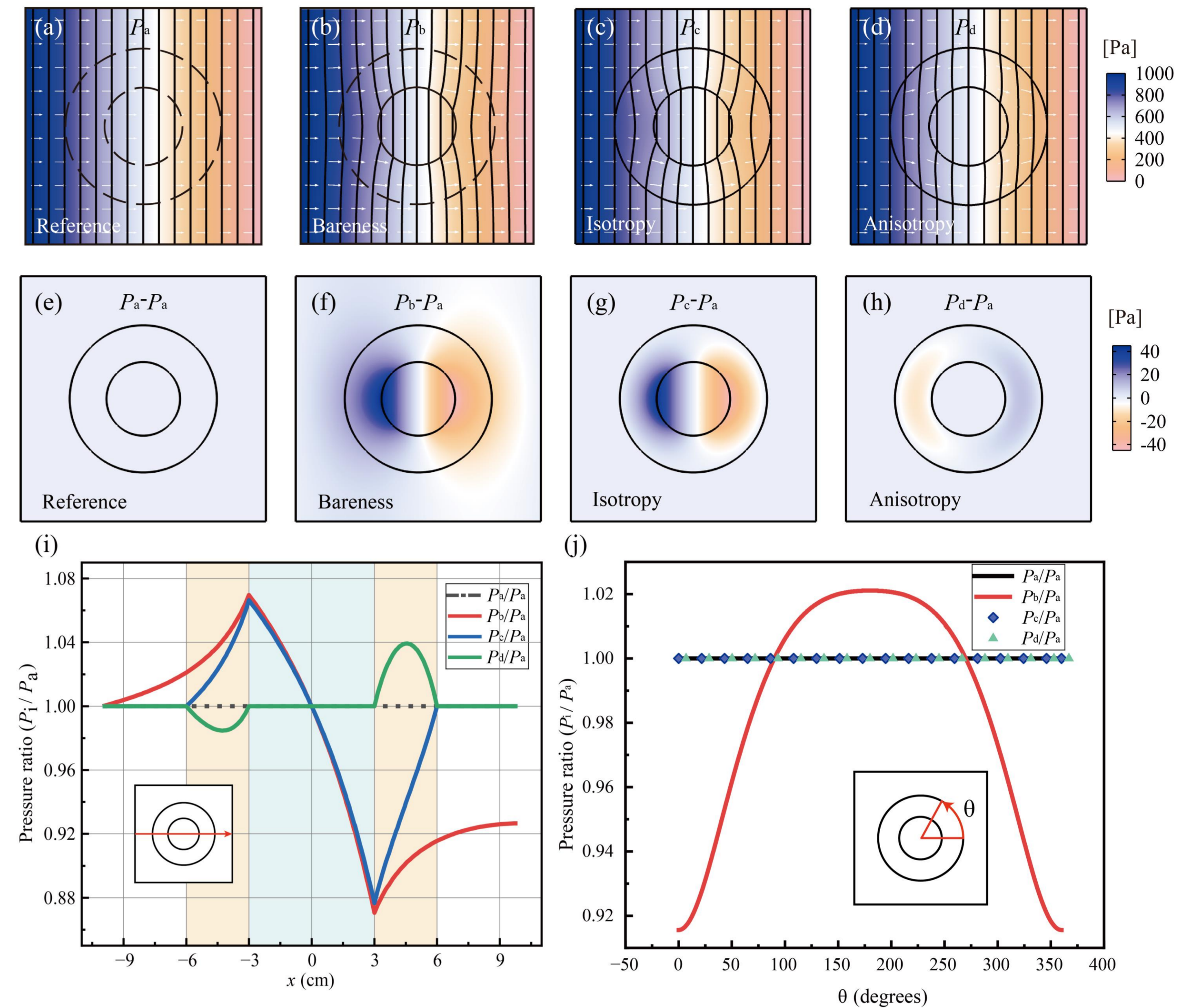


**Methodology:** A multilayer perceptron (MLP) was trained to map microscopic structural parameters to effective macroscopic permeabilities.

**Performance:** Achieved extremely high prediction accuracy with an error of  $< 1\%$  ( $R^2 \approx 1$ ), efficiently navigating the massive, non-linear design space.

## IV Numerical Simulation

Compared four sensing scenarios: **Reference** (ideal), **Bareness** (no shell), **Isotropy** (isotropic shell), and **Anisotropy** (our designed shell).

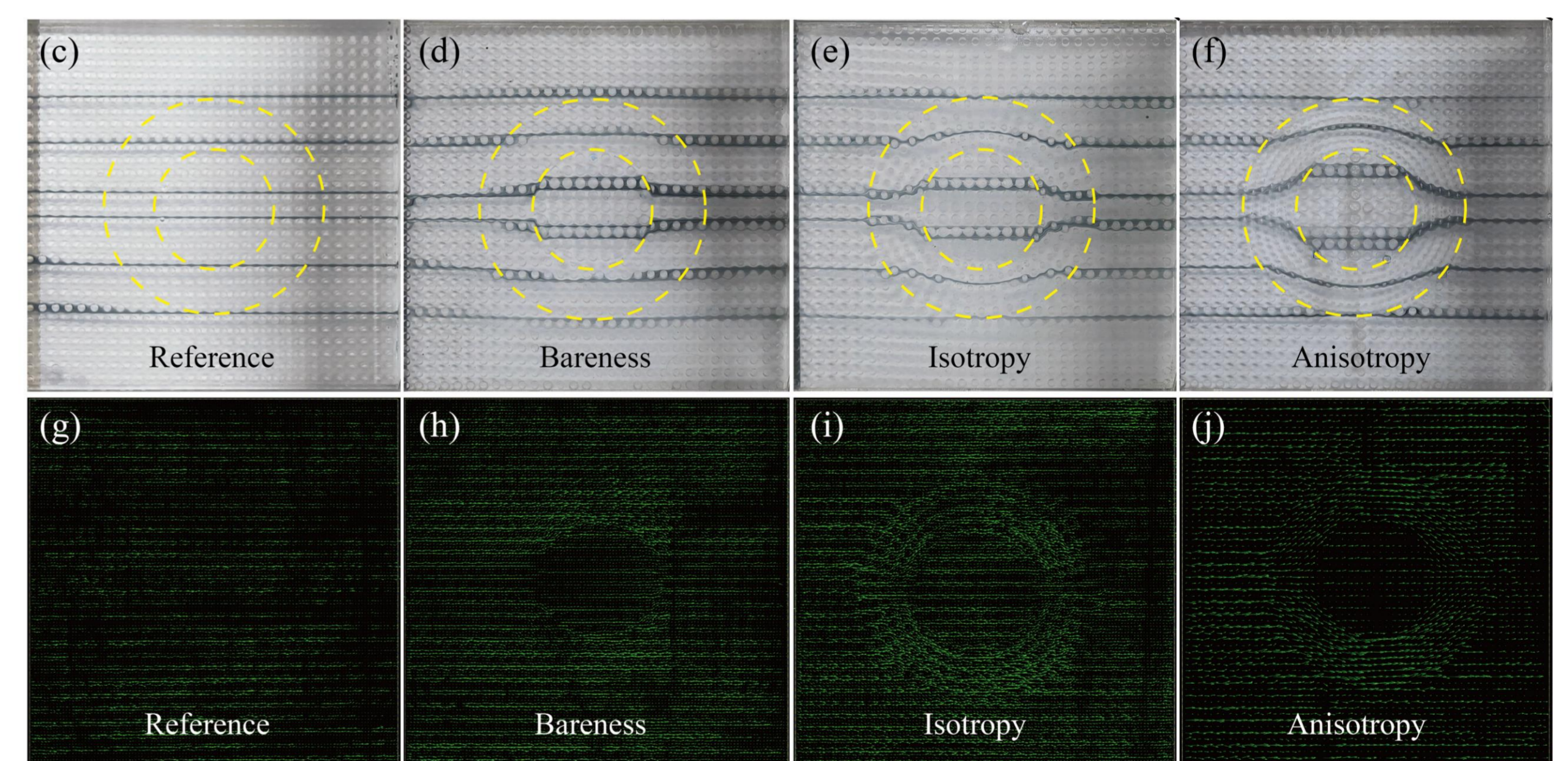


### Key Results:

- The bare sensor severely disrupts the background flow field.
- Our anisotropic metashell perfectly restores the uniform background pressure.
- Measurement errors were reduced by 4 to 5 orders of magnitude compared to bare sensors.

Region	Reference	Bareness	Isotropy	Anisotropy	$\eta$
Core in 2D	0	0.040	$3.8 \times 10^{-2}$	$6.83 \times 10^{-6}$	$1.71 \times 10^{-4}$
Background in 2D	0	0.020	$1.06 \times 10^{-6}$	$1.65 \times 10^{-6}$	$8.25 \times 10^{-5}$
Core in 3D	0	0.023	$2.2 \times 10^{-2}$	$1.94 \times 10^{-6}$	$8.43 \times 10^{-5}$
Background in 3D	0	0.0036	$3.92 \times 10^{-7}$	$9.97 \times 10^{-8}$	$2.77 \times 10^{-5}$

## V Experimental Validation



**Visual Analysis (Dye Tracing):** Pigmented streamlines perfectly matched the simulation, showing no flow distortion around the anisotropic shell.

**Quantitative Analysis:** Particle Image Velocimetry confirmed precise fluid guidance and velocity vector matching.

## VI Conclusion

**Novel Sensing Paradigm:** Anisotropic metashells ensure precise internal measurements while maintaining external flow "invisibility".

**Machine Learning Assisted Optimization:** Leveraged deep learning for rapid and precise inverse design of microstructures, achieving mapping errors of  $< 1\%$ .

### Reference:

Li, Y., Zhou, Y., Wang, Y., Jiang, W., Yang, F., Jin, P., & Huang, J. (2026). Invisible hydrodynamic sensing via metamaterial shells optimized by machine learning. *Advanced Materials*, 38(16), e19721.

