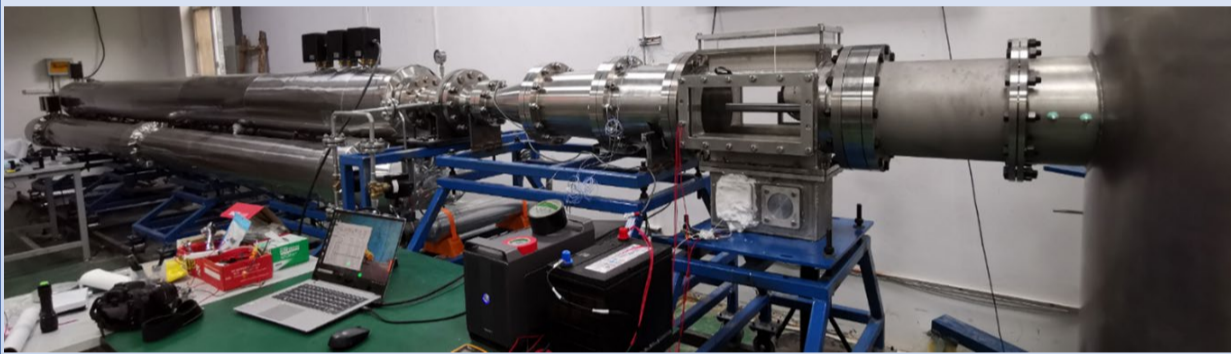


熊有德*, 皮尔卡丹·木合塔尔, 李创创, 吴杰§

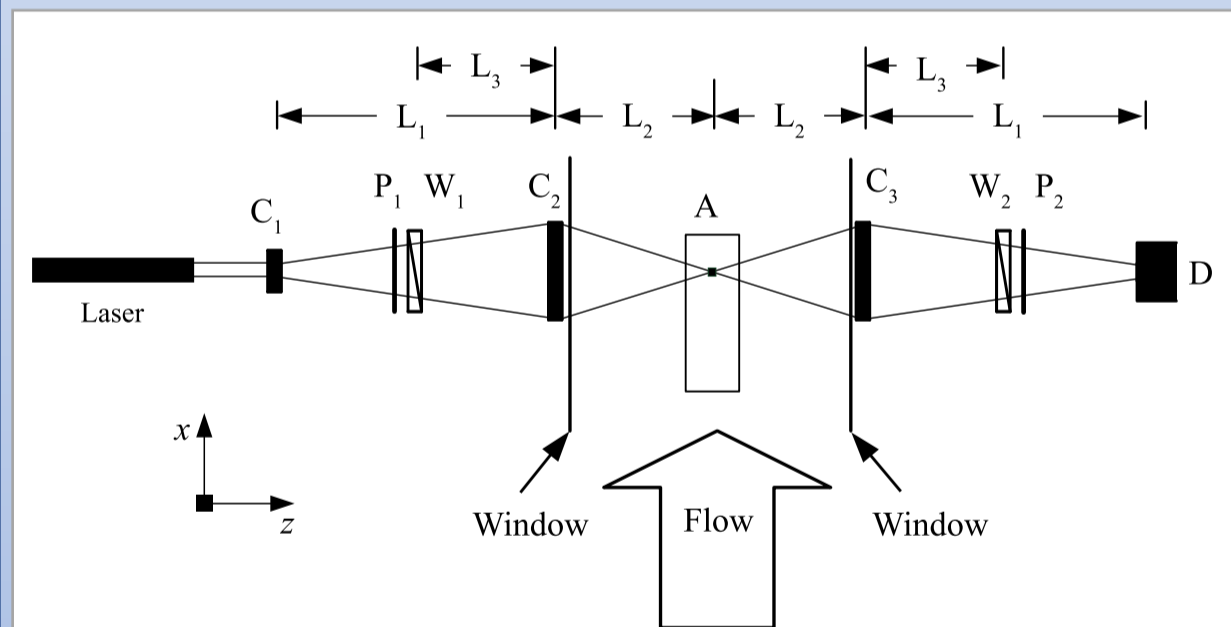
引言

- 高超声速风洞的来流扰动类型和幅值对边界层转换、激波边界层干扰模式等有着重要的影响;
- 聚焦激光差分干涉仪 (FLDI): 相干光干涉; 测量密度扰动; 非介入式; 高时空分辨率 (~10MHz, 0.2mm); 但数据处理困难

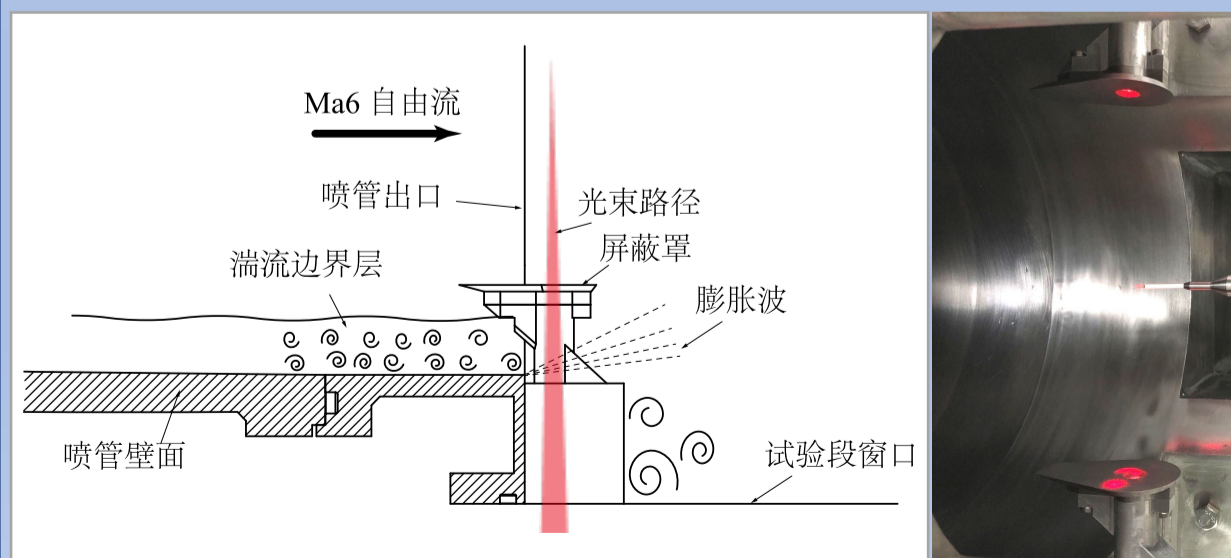
实验设备



华中科技大学马赫六Ludwig风洞



FLDI光路示意图[1]

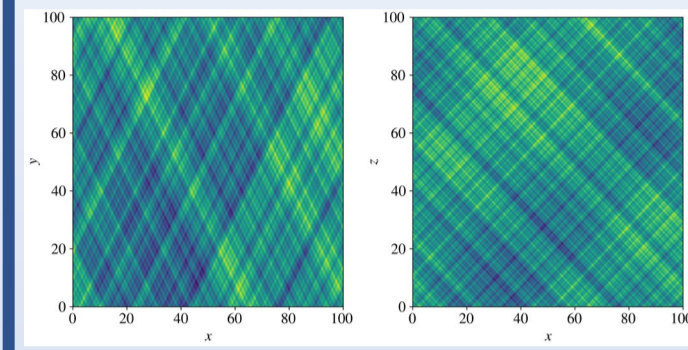


边界层屏蔽罩示意与实物

FLDI传递函数

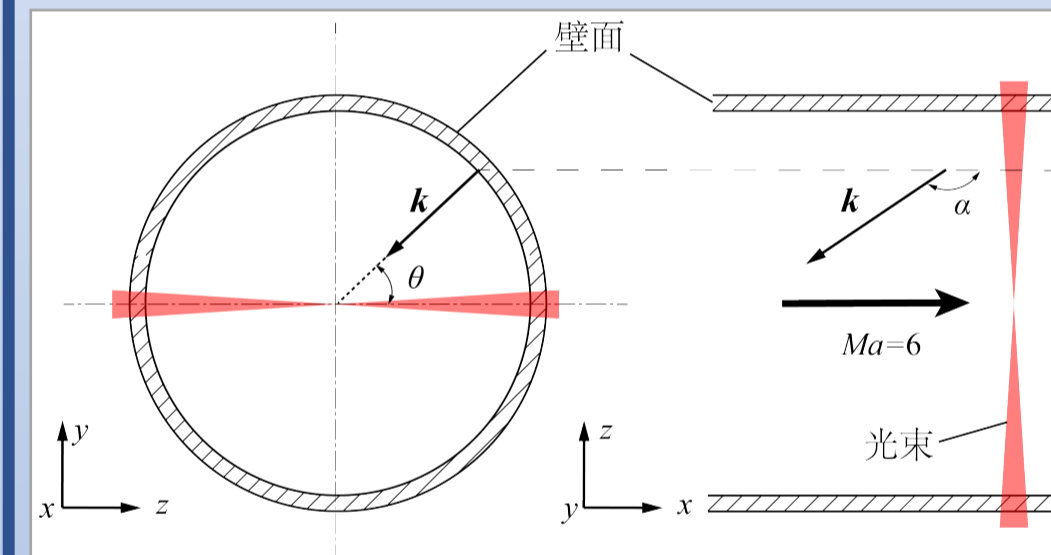
$$\Delta\Phi(t) = A \cdot h(k) \cdot \sin(2\pi ft - \varphi) \quad A = ??$$

$$h(k) = \frac{2\pi}{\lambda_L} \cdot \frac{4\sqrt{2}\pi^{3/2}w_0}{\sqrt{k_x^2 + k_y^2}} \cdot \sin\left(\frac{k_x \Delta x}{2}\right) \cdot \exp\left[-\frac{w_0^2}{8} \left[k_x^2 + k_y^2 + \frac{16\pi^2 k_z^2}{(k_x^2 + k_y^2)\lambda_L^2} \right]\right] \cdot \Re \left[\operatorname{erf} \left(\frac{(k_x^2 + k_y^2)L\lambda_L^2 + i \cdot 4\pi^2 k_z w_0^2}{2\sqrt{2}\pi\sqrt{k_x^2 + k_y^2}\lambda_L w_0} \right) \right]$$



平面扰动[2]

轴对称扰动

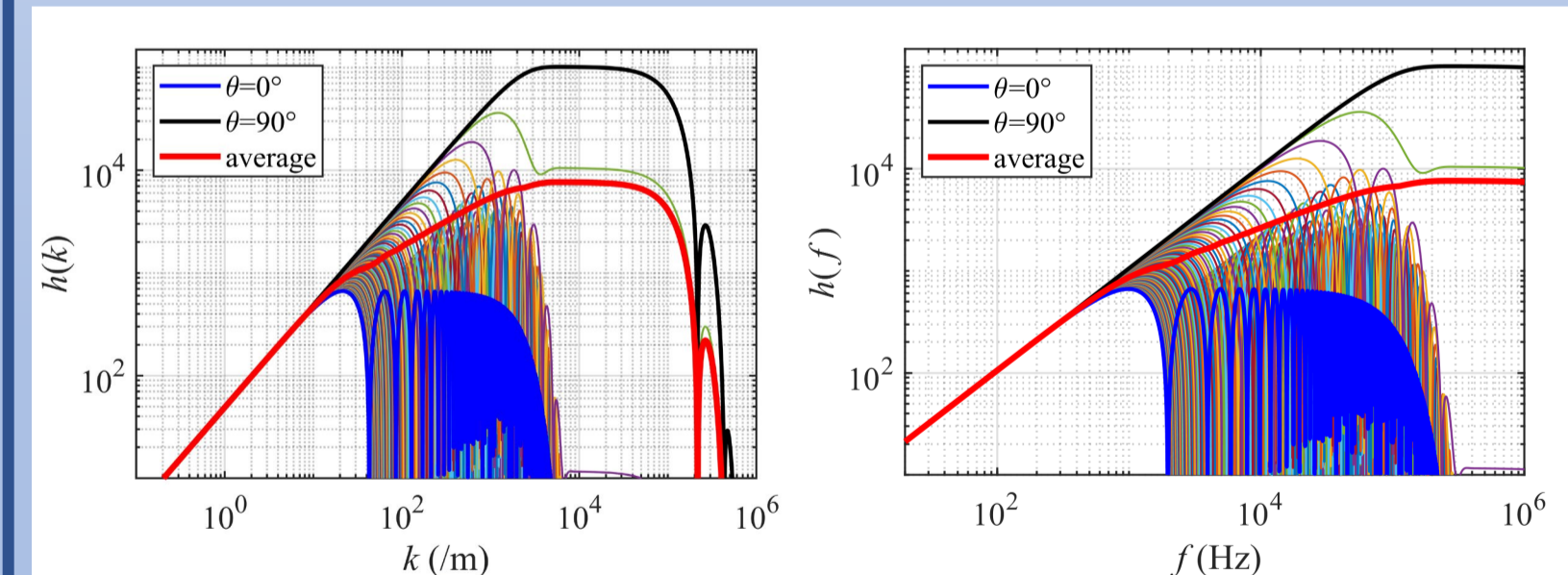


$$k_x = k \cos \alpha$$

$$k_y = k \sin \alpha \sin \theta$$

$$k_z = k \sin \alpha \cos \theta$$

$$h_{av}(k) = \sqrt{\sum_{\theta=0}^{359} |h_{\theta}(k)|^2}$$

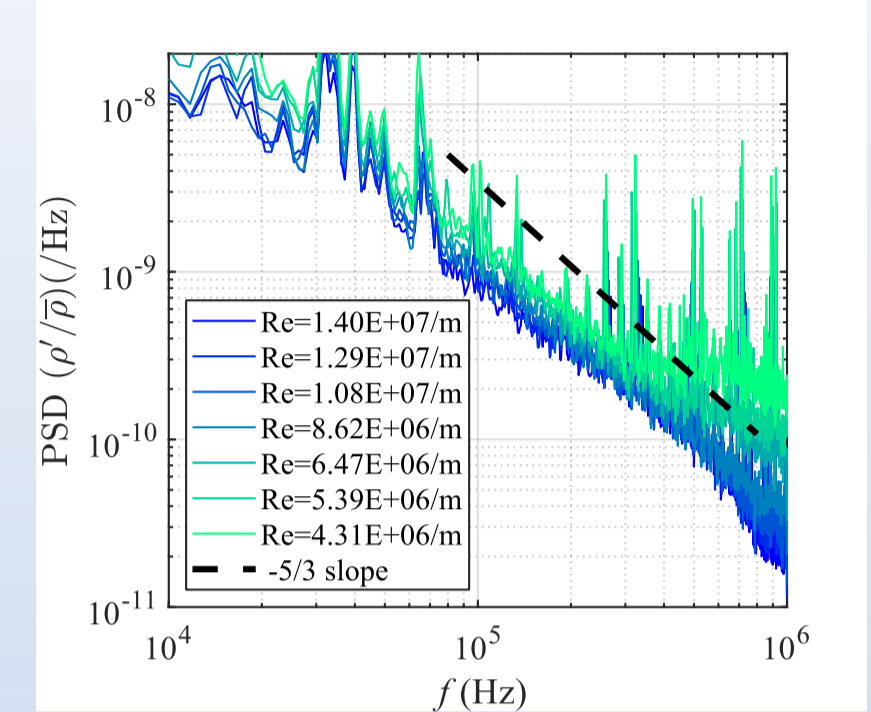


FLDI系统传递函数

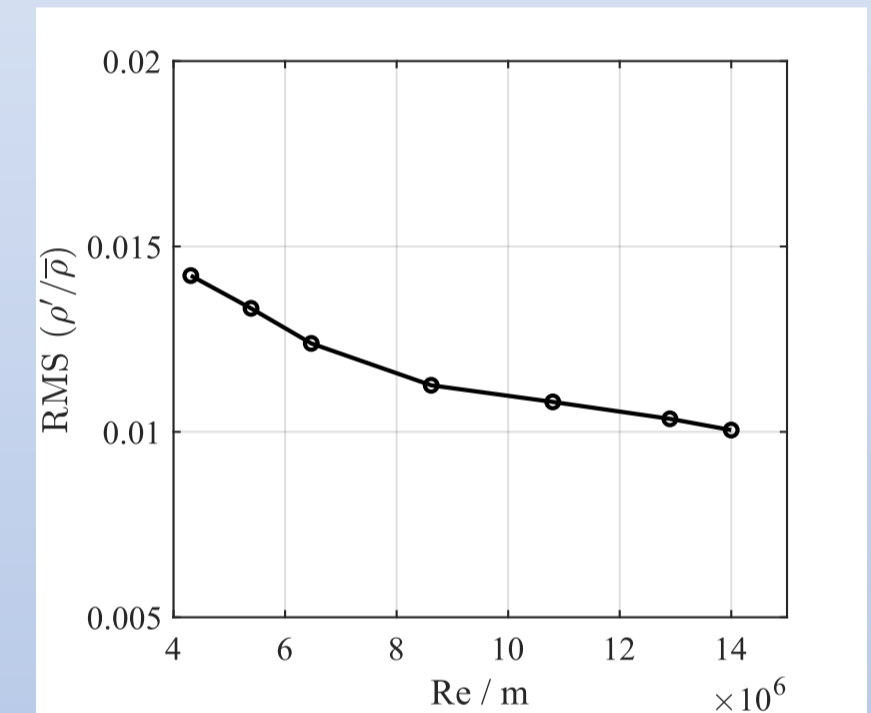
$$\begin{matrix} \div h^2(k) & \div K^2 & \div \bar{\rho}^2 \\ \text{PSD}(\Delta\Phi) \rightleftharpoons \text{PSD}(n') \rightleftharpoons \text{PSD}(\rho') \rightleftharpoons \text{PSD}(\rho' / \bar{\rho}) \\ \times h^2(k) & \times K^2 & \times \bar{\rho}^2 \end{matrix}$$

实验结果

归一化密度扰动频谱



归一化密度扰动均方根



结论

- FLDI光学系统的传递函数在高波数范围主要受90°附近周向角的响应支配; 而低波数区域各周向角区别不大;
- 单位雷诺数增加, 密度脉动绝对值上升, 归一化幅值下降;
- 扰动滚降斜率接近-5/3, 说明处于湍流惯性区范围内。高雷诺数实验中捕捉到了耗散区流动的特征;
- 80~300KHz的密度脉动均方根值约1%~1.4%。