

Tollmien-Schlichting Wave Cancellation Using an Oscillating Lorentz Force

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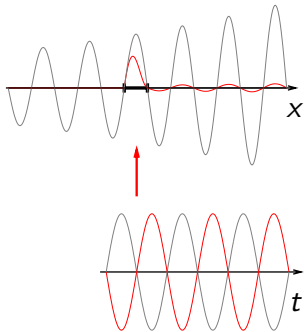


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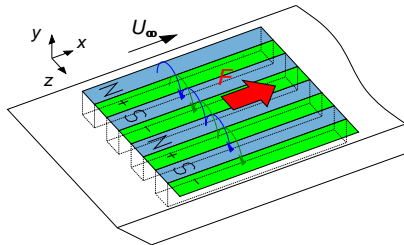
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Motivation

- ▶ TS wave opposition control (Wehrmann 1965, Milling 1981)



- ▶ low electrically conductive fluids (seawater)
- ▶ electric and magnetic field
 \Rightarrow (oscillating) Lorentz force



Outline

Introduction

- Motivation

- Problem description

- Lorentz force

Spanwise averaged force (2-D)

- Wave superposition

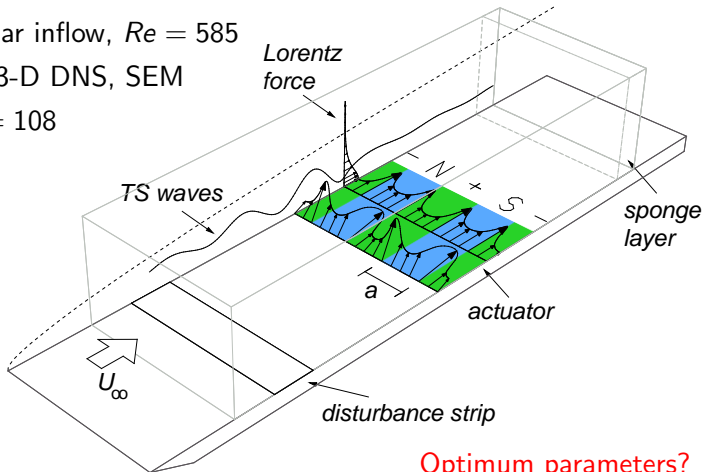
- Parameter variation

- Optimum actuator length

Inhomogeneous force (3-D)

Problem description: Computational domain

- ▶ laminar inflow, $Re = 585$
- ▶ 2-D/3-D DNS, SEM
- ▶ $F^+ = 108$



Optimum parameters?

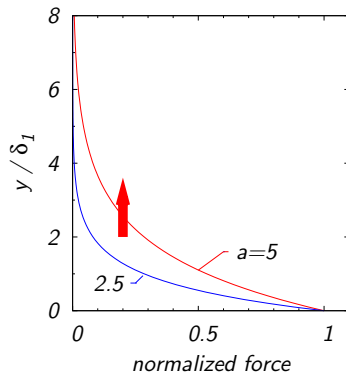
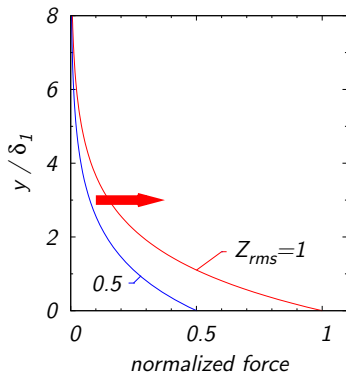
3-D force \Leftrightarrow control 2-D waves?

Lorentz force: Two parameters Z_{rms} , a

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} + \mathbf{F} \sin(\omega t), \quad \mathbf{F} \sim Z \exp(-\pi y/a) \mathbf{e}_x$$

F. amplitude $Z_{rms} = \frac{j_{0,rms} M_0 a^2}{8\pi \rho U_\infty \nu}$

Penetration depth a



Introduction

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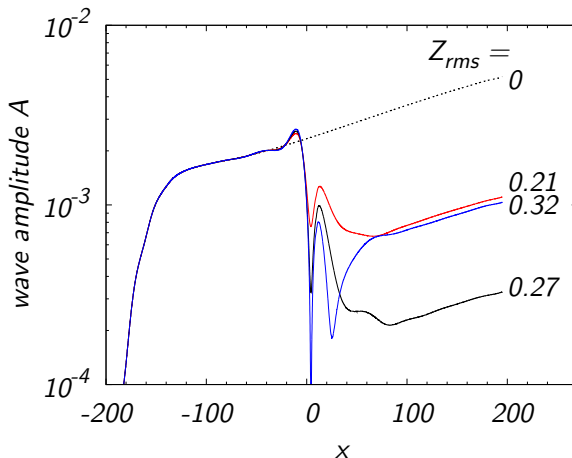
Wave superposition

Parameter variation

Optimum actuator length

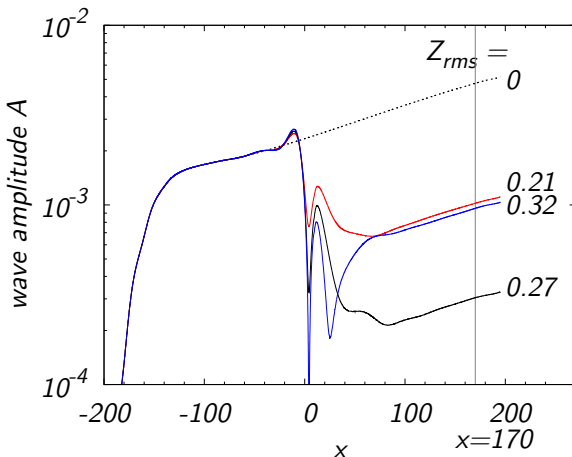
Inhomogeneous force (3-D)

Wave superposition



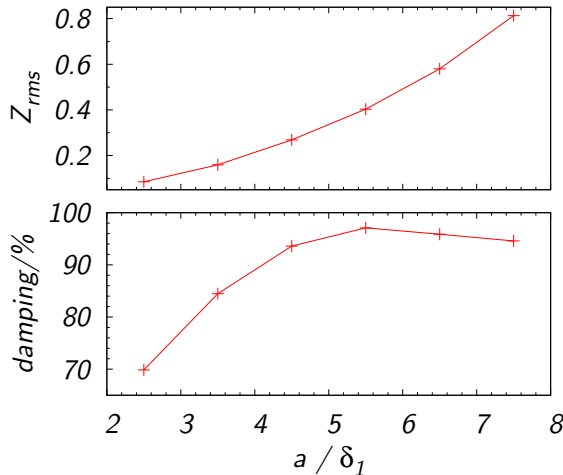
- ▶ for $a = 4.5$:
best $Z_{rms} = 0.27$
- ▶ max. rms-value
of $u'(x)$
 \Rightarrow wave
amplitude A

Wave superposition



- ▶ for $a = 4.5$:
best $Z_{rms} = 0.27$
- ▶ max. rms-value
of $u'(x)$
 \Rightarrow wave
amplitude A
- ▶ damping
measured at
 $x = 170$: 95%

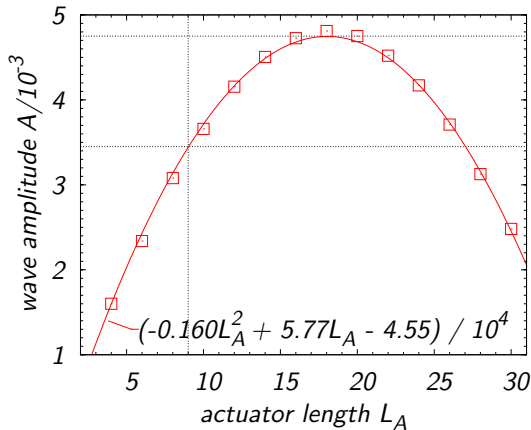
Variation of penetration depth a



damping:

- ▶ global max. 97%
at $a = 5.5$,
 $Z_{rms} = 0.4$
- ▶ $> 90\%$
for $4.5 \leq a \leq 7.5$

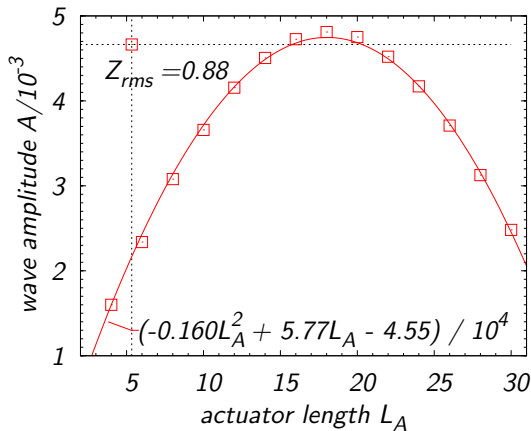
Variation of actuator length L_A



- ▶ actuation only
- ▶ max. amplitude if $L_A = \frac{1}{2}\lambda = 18$
- ▶ amplitude $A \sim (-L_A^2)$
- ▶ elec. power required $P \sim L_A \cdot Z_{rms} \Rightarrow$ optimization

$$a = 5.5, Z_{rms} = 0.4$$

Optimum actuator length



$$a = 5.5, Z_{rms} = 0.4$$

- ▶ elec. power required
 $P \sim L_A \cdot Z_{rms}$
- ▶ wave amplitude
 $A \sim Z_{rms}, A \sim (-L_A^2)$
- ▶ $\min_{L_A} P = L_A \frac{A(18)}{A(L_A)}$
- ▶ optimum:
 $L_A = 5.33 \approx \frac{1}{7} \lambda$
- ▶ $\frac{\hat{u}'_{rms}(18)}{\hat{u}'_{rms}(5.33)} = 2.2$

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Spanwise averaged force (2-D)

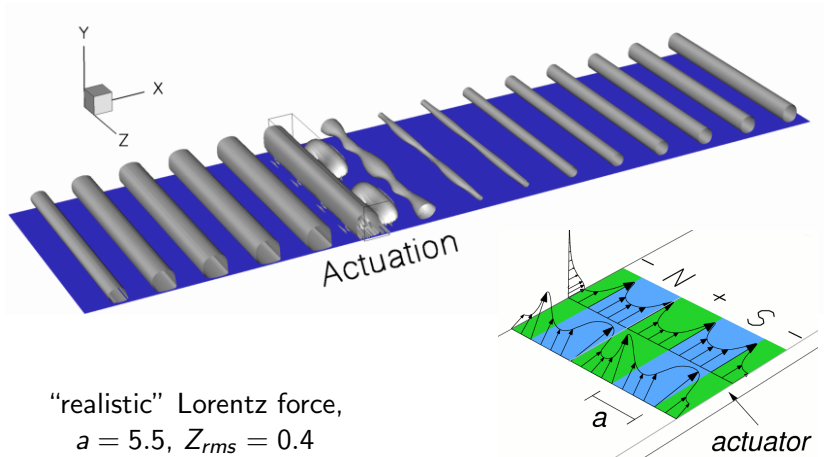
- Wave superposition

- Parameter variation

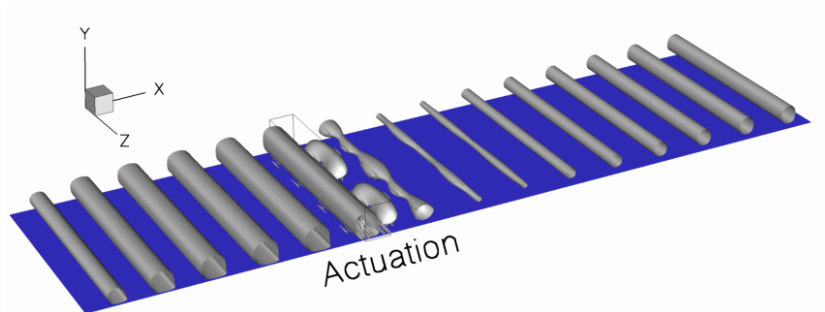
- Optimum actuator length

Inhomogeneous force (3-D)

Wave cancellation using inhomogeneous force (3-D)



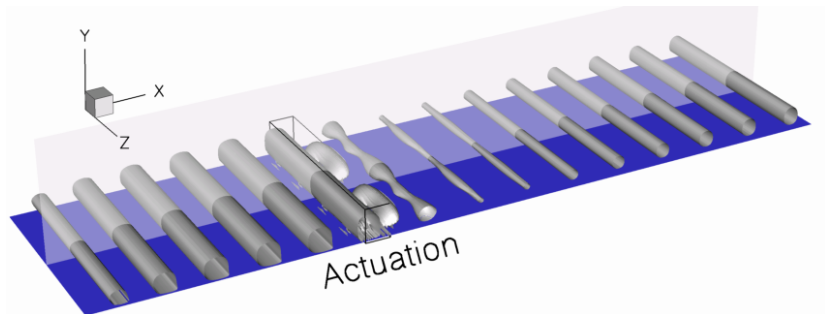
Wave cancellation using inhomogeneous force (3-D)



vortex visualization by λ_2

“realistic” Lorentz force, $a = 5.5$, $Z_{rms} = 0.4$

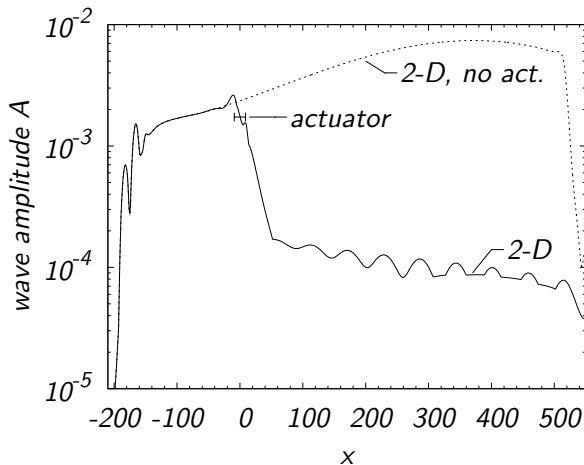
Wave cancellation using inhomogeneous force (3-D)



vortex visualization by λ_2

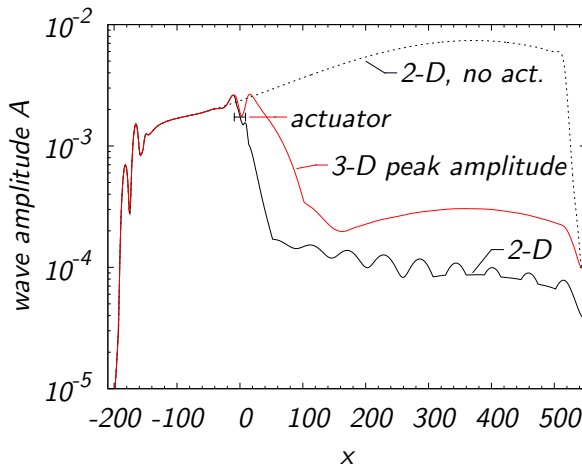
“realistic” Lorentz force, $a = 5.5$, $Z_{rms} = 0.4$

Wave cancellation using inhomogeneous force (3-D)



“realistic” Lorentz force, $a = 5.5$, $Z_{rms} = 0.4$

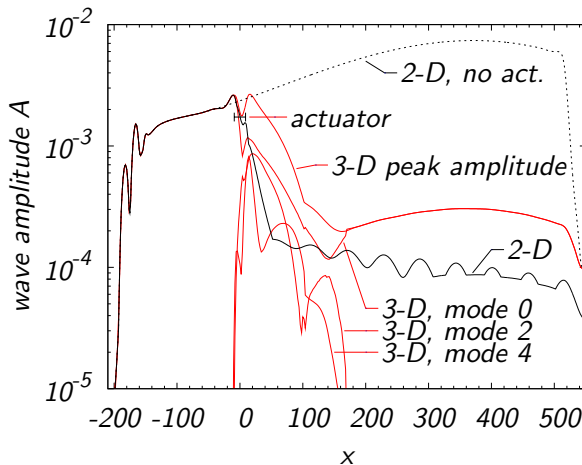
Wave cancellation using inhomogeneous force (3-D)



► damping delayed

“realistic” Lorentz force, $a = 5.5$, $Z_{rms} = 0.4$

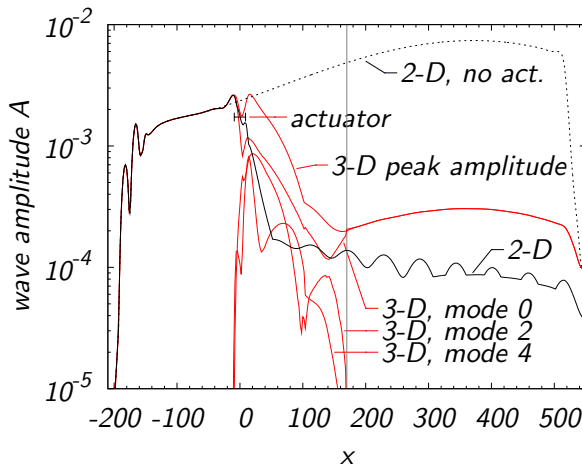
Wave cancellation using inhomogeneous force (3-D)



- ▶ damping delayed
- ▶ spanwise modes rise & decay

“realistic” Lorentz force, $a = 5.5$, $Z_{rms} = 0.4$

Wave cancellation using inhomogeneous force (3-D)



- ▶ damping delayed
- ▶ spanwise modes rise & decay
- ▶ damping at $x = 170$: 95%
(2-D: 97%)

“realistic” Lorentz force, $a = 5.5$, $Z_{rms} = 0.4$

Conclusion

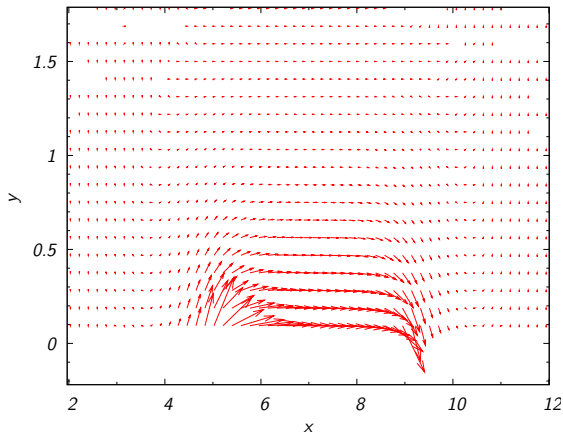
Oscillating Lorentz force

- ▶ can reduce TS wave amplitude
- ▶ maximum damping 97% (2-D) at $a = 5.5$ and $Z_{rms} = 0.4$
- ▶ optimum actuator length $\approx \frac{1}{7}\lambda$
- ▶ more realistic force distribution: 94% (3-D)

Thank you.
Questions?

Is detailed actuator modelling necessary?

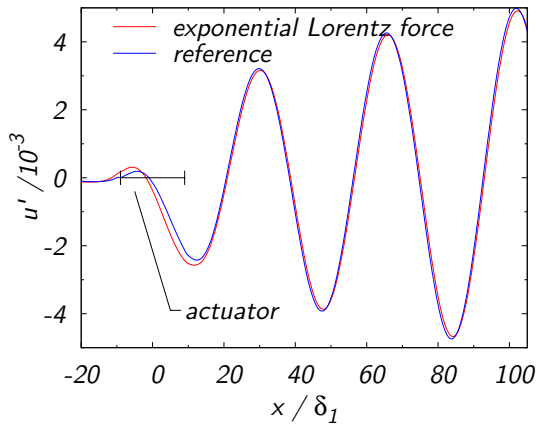
spanwise averaged Lorentz force:



► $\mathbf{F}_L = \sigma \mathbf{E} \times \mathbf{B}$

► $\mathbf{F}_L \approx N e^{-\pi y/a} \mathbf{e}_x$

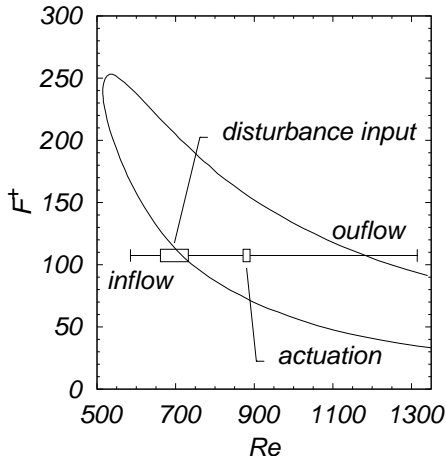
Is detailed actuator modelling necessary?



- ▶ small phase shift 3.5°
- ▶ damping: 94% (reference: 97%)

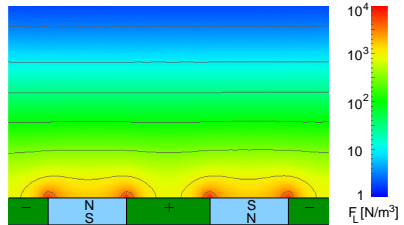
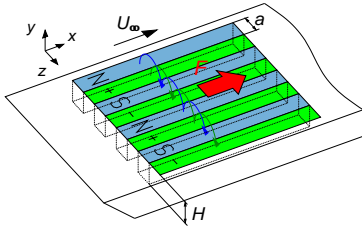
$(L_A = 18)$

Problem description: Relative to neutral stability curve



- ▶ $F^+ = 108$
- ▶ laminar inflow at $Re = 585$
- ▶ disturbance input at $Re \approx 700$
- ▶ actuation at $Re \approx 880$

Lorentz force: Actuator geometry



low elec. conductive media:

$$\mathbf{F} = \mathbf{j} \times \mathbf{B} = F \mathbf{e}_x$$

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B})$$

$$\phi = E_0 / (U_\infty B_0) \gg 1$$

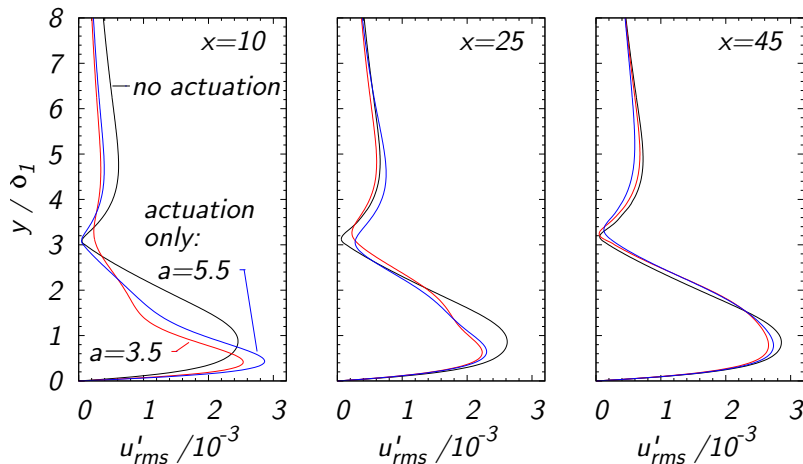
$$\bar{F} = \frac{\pi}{8} j_0 M_0 e^{-\frac{\pi}{a} y}$$

Gailitis, Lielausis 1961

$$u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = \frac{\partial^2 u^*}{\partial y^{*2}} + Z e^{-y^*}$$

$$Z = \frac{j_0 M_0 a^2}{8 \pi \rho U_\infty \nu} = 1 : \quad \frac{u}{U_\infty} = 1 - e^{-\frac{\pi}{a} y}$$

Evolution of the cancelling wave



Dimensionless numbers

- Navier-Stokes

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} + N \exp(-\pi y/a) \mathbf{e}_x$$

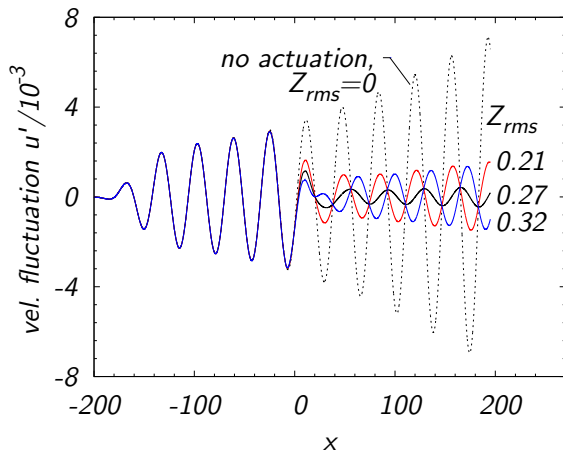
- Interaction parameter

$$N = \frac{\text{Lorentz f.}}{\text{inertial f.}} = \frac{j_0 B_0 l}{\rho U_\infty^2} \qquad N = \frac{Z}{Re} \left(\frac{\pi}{a/\delta} \right)^2$$

- modified Hartmann number

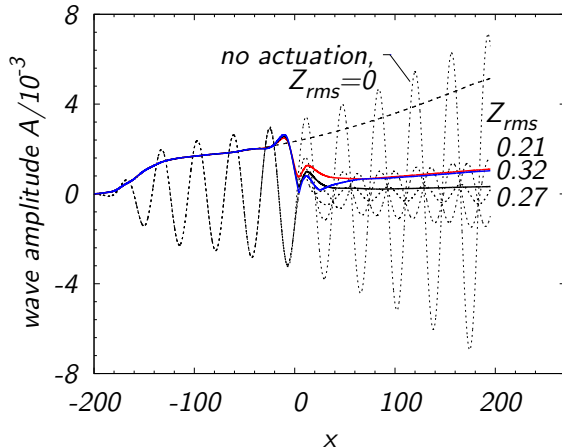
$$Z = \frac{\text{Lorentz f.}}{\text{viscous f.}} = \frac{j_0 M_0 a^2}{8\pi \rho U_\infty \nu}$$

Wave superposition



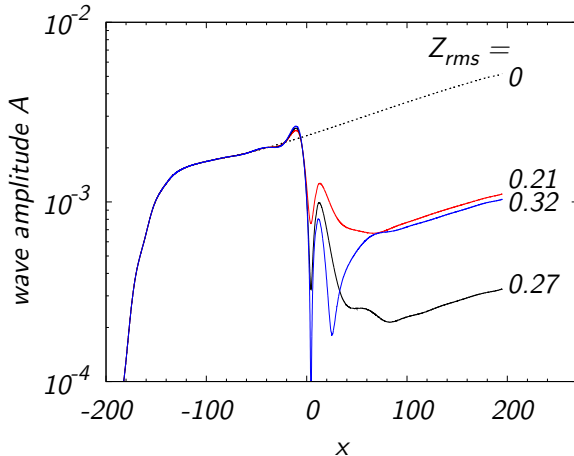
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Wave superposition



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References



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