Turbulent drag reduction with streamwise travelling waves in the compressible regime

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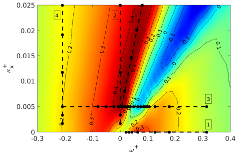


Skin friction drag reduction with spanwise forcing

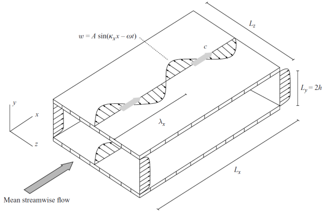
Streamwise-travelling waves of spanwise wall velocity

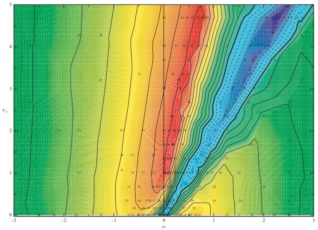
$$W(x,t) = A sin(\kappa_x x - \omega t)$$

Oscillating wall: $\kappa_x = 0$

Steady wave: $\omega = 0$

$$\text{Drag reduction}(\mathcal{DR}) = 1 - \frac{C_f}{C_{f,0}}$$





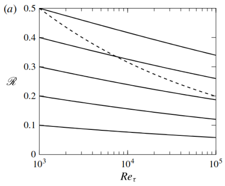
$Re_\tau = 200, A^+ = 12, DR_{max} = 48\%$

Quadrio et al. JFM 2009

Towards real world applications

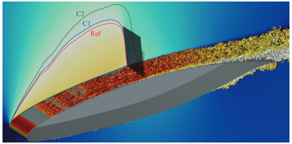
Dependence on:

- Reynolds number



Gatti & Quadrio JFM 2016

- Complex shape and other drag sources



Quadrio et al. JFM 2022

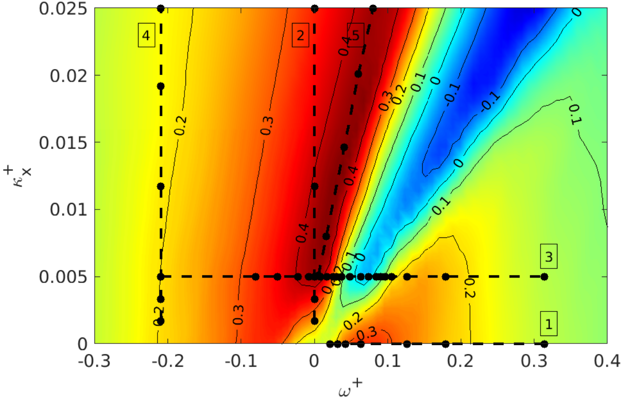
- Mach number

≈ Yao & Hussain 2019

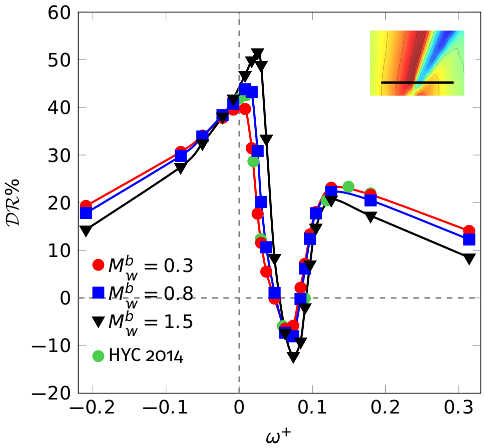
Simulation: parameters

- Direct Numerical Simulations
- Channel flow
- STREAmS solver (Bernardini et al. CPC 2021)
- Constant flow rate (CFR) : $U_b = const$
- $Re_\tau = 400$
- Parameters:
    - Mach: $M_w^b = U_b/c_w$ = $U_b/\sqrt{\gamma R T_w} = 0.3, 0.8, 1.5$ (as Yao & Hussain JFM 2019)
    - Control: $A^+ = 12$, 42 combinations of (ω^+, κ_x^+)

Simulation: control map



Results: Travelling waves at $\kappa_x = 0.005$



$DR_{M=0.3} \approx 40$ % $DR_{M=1.5} \approx 52$ %

Compressibility effect ($M_w^b \uparrow$):

- Negative effect at large $|\omega|$
- Negative effect in the drag increase zone
- Large positive effect at small ω

Question

- Travelling waves still work in compressible regime
- Compressibility has a positive effect on $\mathcal{DR}$

Question

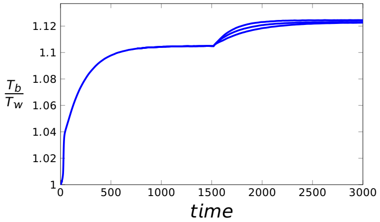
- Travelling waves still work in compressible regime
- Compressibility has a positive effect on $\mathcal{DR}$

Is the increase of $\mathcal{DR}$ actually due to compressibility?

The effect of the temperature

- $T_b \uparrow$ with control depending on (ω, κ_x)

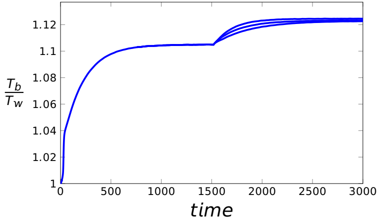
$$T_b = \frac{1}{2h\rho_b U_b}\int_{-h}^{h} \langle \rho u T \rangle \, dy$$



The effect of the temperature

- $T_b \uparrow$ with control depending on (ω, κ_x)

$$T_b = \frac{1}{2h\rho_b U_b} \int_{-h}^{h} \langle \rho u T \rangle \, dy$$

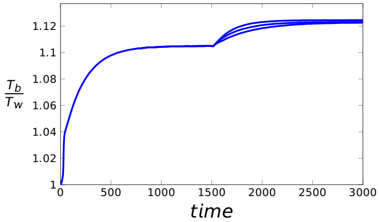


Compressibility or inderect $T_b \uparrow$?

The effect of the temperature

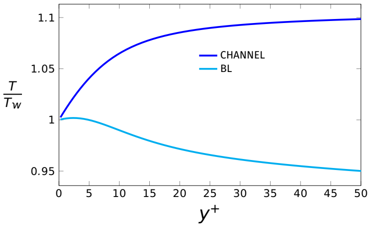
- $T_b \uparrow$ with control depending on (ω, κ_x)

$$T_b = \frac{1}{2h\rho_b U_b}\int_{-h}^{h} \langle \rho u T \rangle \, dy$$



Compressibility or inderect $T_b \uparrow$?

- T profile not representative of external flows



New comparison strategy

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho (e + p/\rho) u_j}{\partial x_j} = \frac{\partial \sigma_{ij} u_i}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + f u_1$$

New comparison strategy

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho (e + p/\rho) u_j}{\partial x_j} = \frac{\partial \sigma_{ij} u_i}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + f u_1$$

Zero Bulk Cooling (ZBC)

New comparison strategy

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho (e + p/\rho) u_j}{\partial x_j} = \frac{\partial \sigma_{ij} u_i}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + f u_1 - \Phi$$

Zero Bulk Cooling (ZBC)

Φ=0

Constained Bulk Cooling (CBC)

Φ=f(Θ=const)

New comparison strategy

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho (e + p/\rho) u_j}{\partial x_j} = \frac{\partial \sigma_{ij} u_i}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + f u_1 - \Phi$$

Zero Bulk Cooling (ZBC)

Φ=0

Constained Bulk Cooling (CBC)

Φ=f(Θ=const)

Diabatic Parameter (Θ)

$$\Theta = \frac{T_w - T_b}{T_r - T_b}$$

$$T_r = \left(1 + \frac{\gamma - 1}{2} r (M_w^b)^2\right) T_b$$

Θ= Fraction of the available kinetic energy transformed into thermal energy at the wall

New comparison strategy

We decouple compressibility from purely thermodynamical effects

Zero Bulk Cooling (ZBC)

$\ominus$ varies

$\downarrow$

T_b varies

Constained Bulk Cooling (CBC)

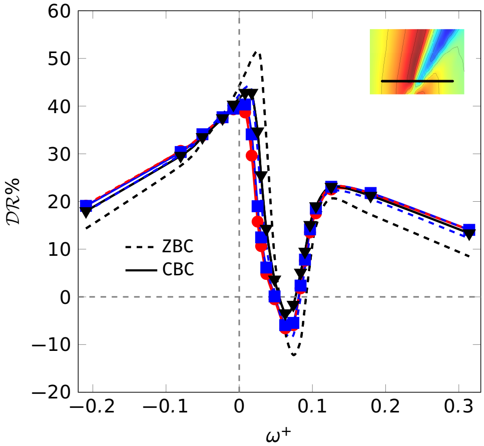
$\ominus$ constant = 0.75

$\downarrow$

T_b

- constant across control
- varies across Mach

Drag reduction: ZBC vs CBC



$DR_{M=0.3} \approx 40\ \%$ $\quad DR^{ZBC}_{M=1.5} \approx 52\ \%$ $\quad DR^{CBC}_{M=1.5} \approx 43\ \%$

Conclusions

- Influence of compressibility to the drag reduction performance of the streamwise-travelling waves of spanwise wall motion
- Two different comparison strategies:
  - Zero Bulk Cooling: Θ=variable
  - Constrained Bulk Cooling: Θ=const to decouple compressibility from purely thermodynamic effects

- Travelling waves still work in the compressible regime
- Compressibility effectiveness:
  - ZBC: large improvement
  - CBC: marginal improvement

Extension: Power budget

Drag reduction($\mathcal{DR}$)

$$\mathcal{DR} = 1 - \frac{C_f}{C_{f,0}}.$$

Input/control power (P_{in})

$$P_{in} = \frac{1}{P_0^*} \frac{1}{T_{ave} L_x L_z} \int_{t_i}^{t_f} \int_0^{L_x} \int_0^{L_z} W \, \tau_z \, dx \, dz \, dt$$

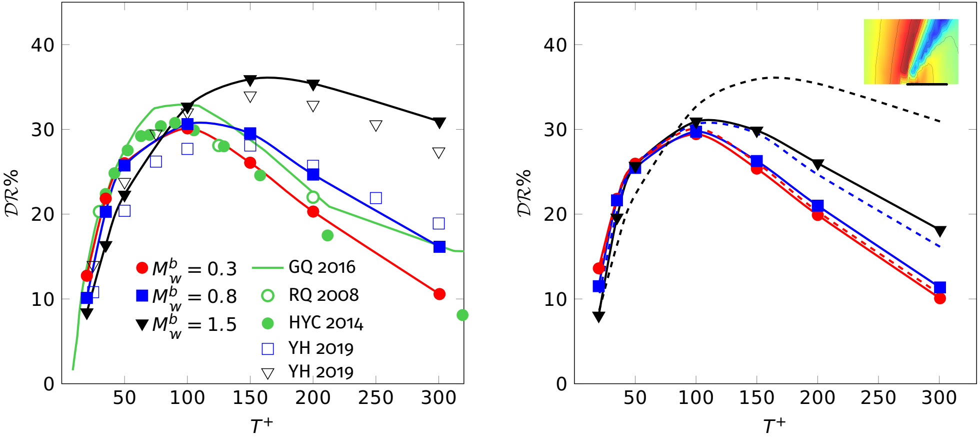
Pumping Power

$$P^* = \frac{U_b}{T_{ave} L_x L_z} \int_{t_i}^{t_f} \int_0^{L_x} \int_0^{L_z} \tau_x \, dx \, dz \, dt$$

Net energy saving rate (P_{net})

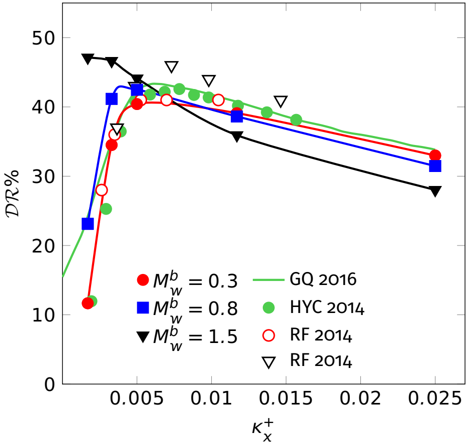
$$P_{net} = \mathcal{DR} - P_{in}.$$

Line 1

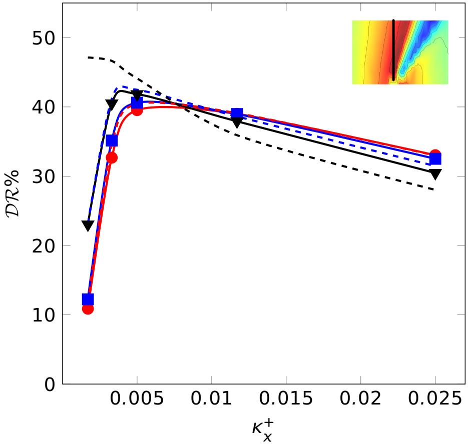


40
30
20
10
0
50
100
150
200
250
300
T^+
$\mathcal{DR}\%$
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016
RQ 2008
HYC 2014
YH 2019
YH 2019

Line 2

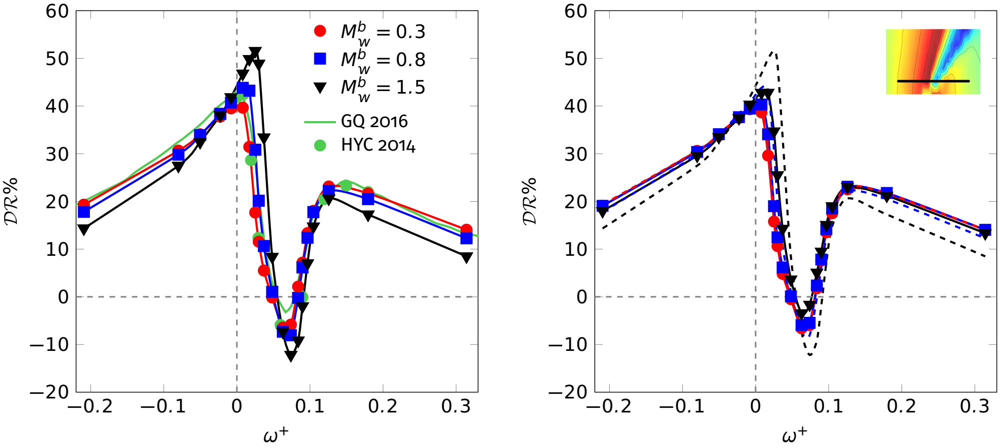


50
40
30
20
10
0
0.005
0.01
0.015
0.02
0.025
κ_x^+
$\mathcal{DR}\%$
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016
HYC 2014
RF 2014
RF 2014

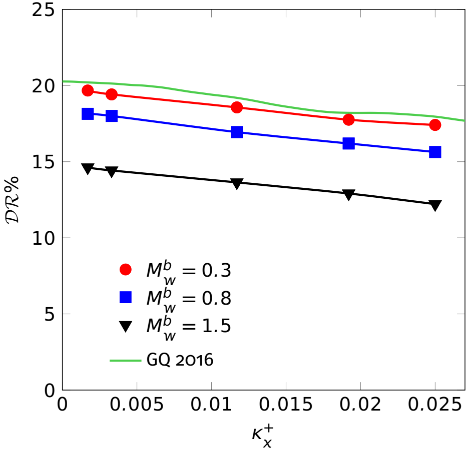


50
40
30
20
10
0
0.005
0.01
0.015
0.02
0.025
κ_x^+
$\mathcal{DR}\%$

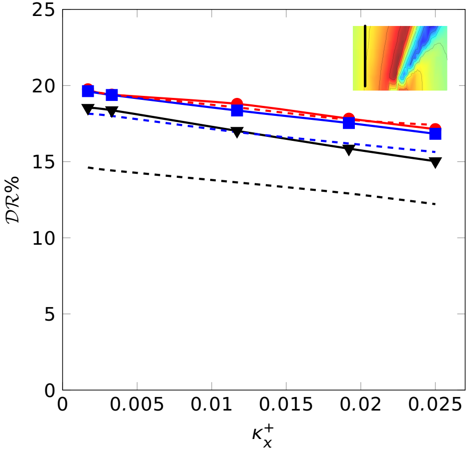
Line 3



Line 4

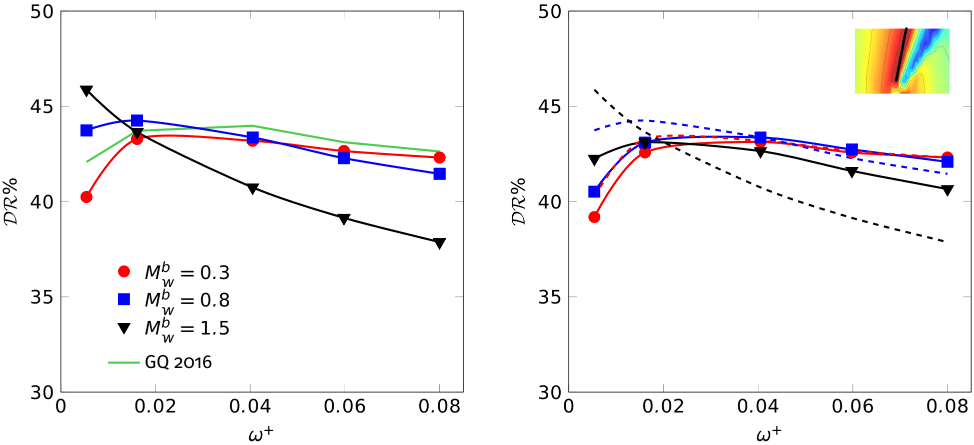


25
20
15
10
5
0
$\mathcal{DR}\%$
0
0.005
0.01
0.015
0.02
0.025
κ_x^+
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016



25
20
15
10
5
0
$\mathcal{DR}\%$
0
0.005
0.01
0.015
0.02
0.025
κ_x^+

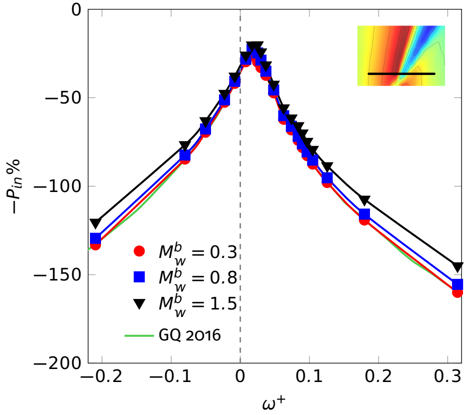
Line 5



50
45
40
35
30
0
0.02
0.04
0.06
0.08
$\mathcal{DR}\%$
ω^+
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016

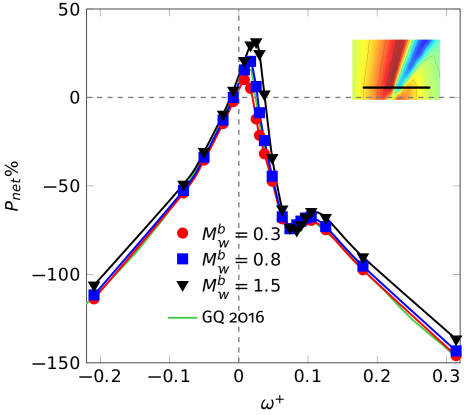
Results: Power budgets

Input/control power



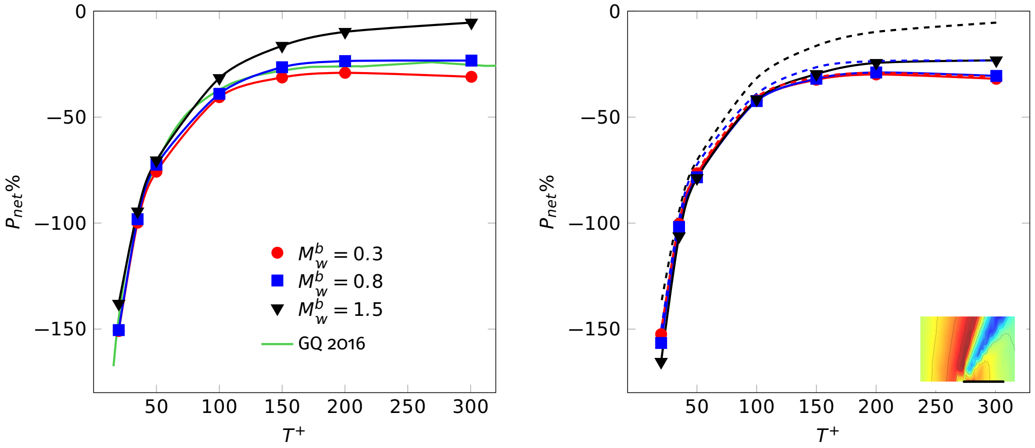
$$P_{in} = \frac{1}{P_0^*}\frac{1}{T_{ave}L_xL_z}\int_{t_i}^{t_f}\int_0^{L_x}\int_0^{L_z} W\,\tau_z\,dx\,dz\,dt$$

Net saving



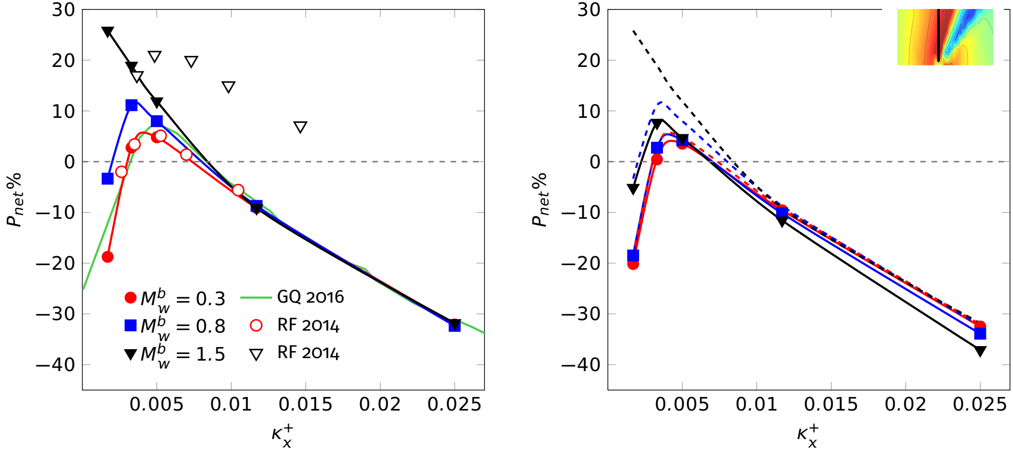
$$P_{net} = \mathcal{DR} - P_{in}$$

Line 1

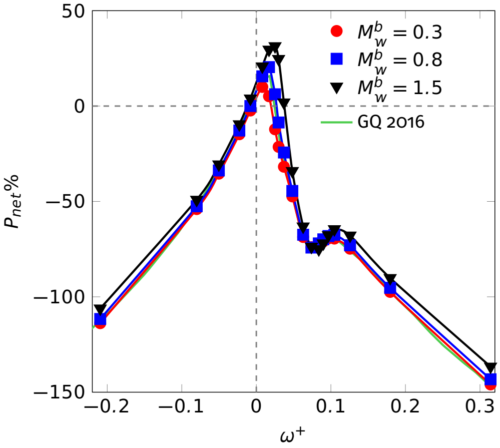


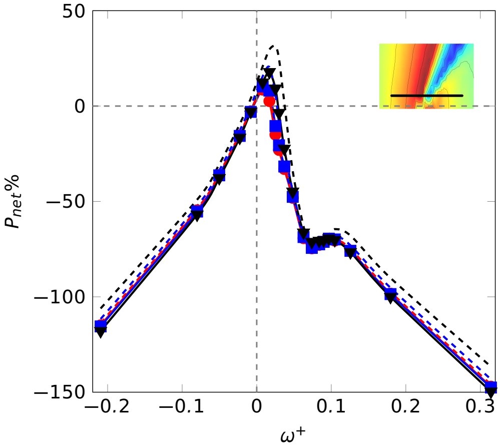
0
−50
−100
−150
$P_{net}\%$
50
100
150
200
250
300
T^+
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016

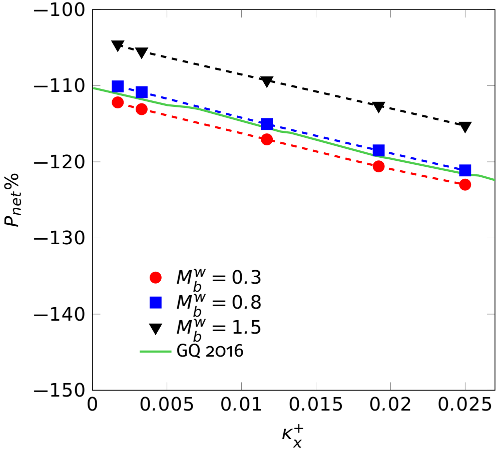
Line 2


30
20
10
0
−10
−20
−30
−40
P_{net}%
0.005
0.01
0.015
0.02
0.025
κ_x^+
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016
RF 2014
RF 2014

Line 3


50
0
−50
−100
−150
$P_{net}\%$
−0.2
−0.1
0
0.1
0.2
0.3
ω^+
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
GQ 2016


50
0
−50
−100
−150
$P_{net}\%$
−0.2
−0.1
0
0.1
0.2
0.3
ω^+


−100
−110
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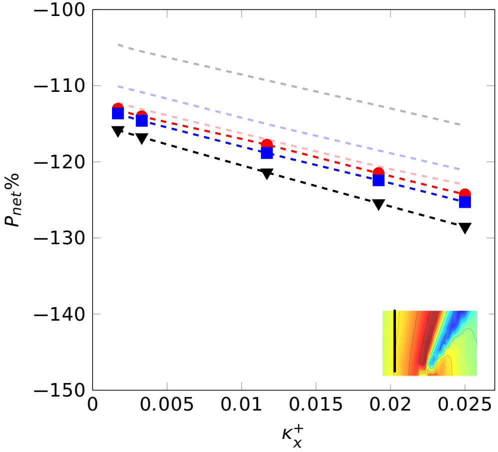
−140
−150
0
0.005
0.01
0.015
0.02
0.025
$P_{net}\%$
κ_x^+
$M_b^w = 0.3$
$M_b^w = 0.8$
$M_b^w = 1.5$
GQ 2016


−100
−110
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0.005
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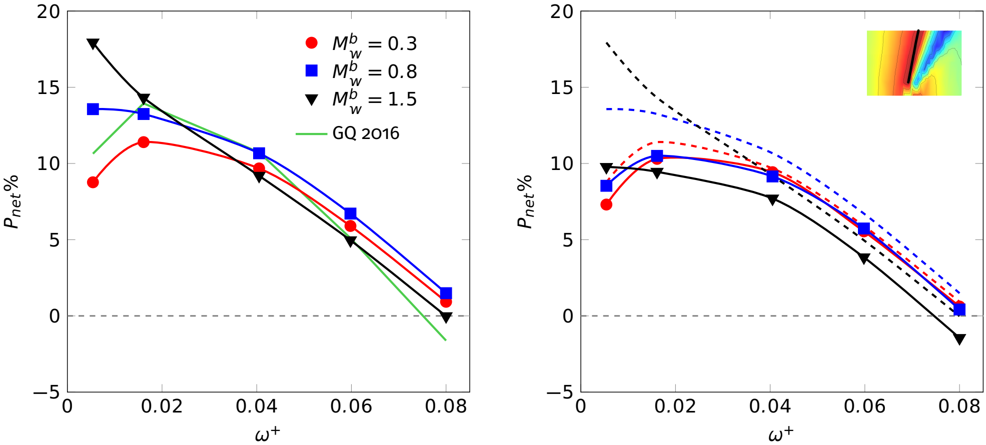
0.015
0.02
0.025
$P_{net}\%$
κ_x^+

Line 5



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0.02
0.04
0.06
0.08
ω^+
$P_{net}\%$
$M_w^b = 0.3$
$M_w^b = 0.8$
$M_w^b = 1.5$
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