Intrinsic thermoacoustic feedback
and its consequences for combustion noise and combustion dynamics

Wolfgang Polifke

POLKA 4th Progress Meeting

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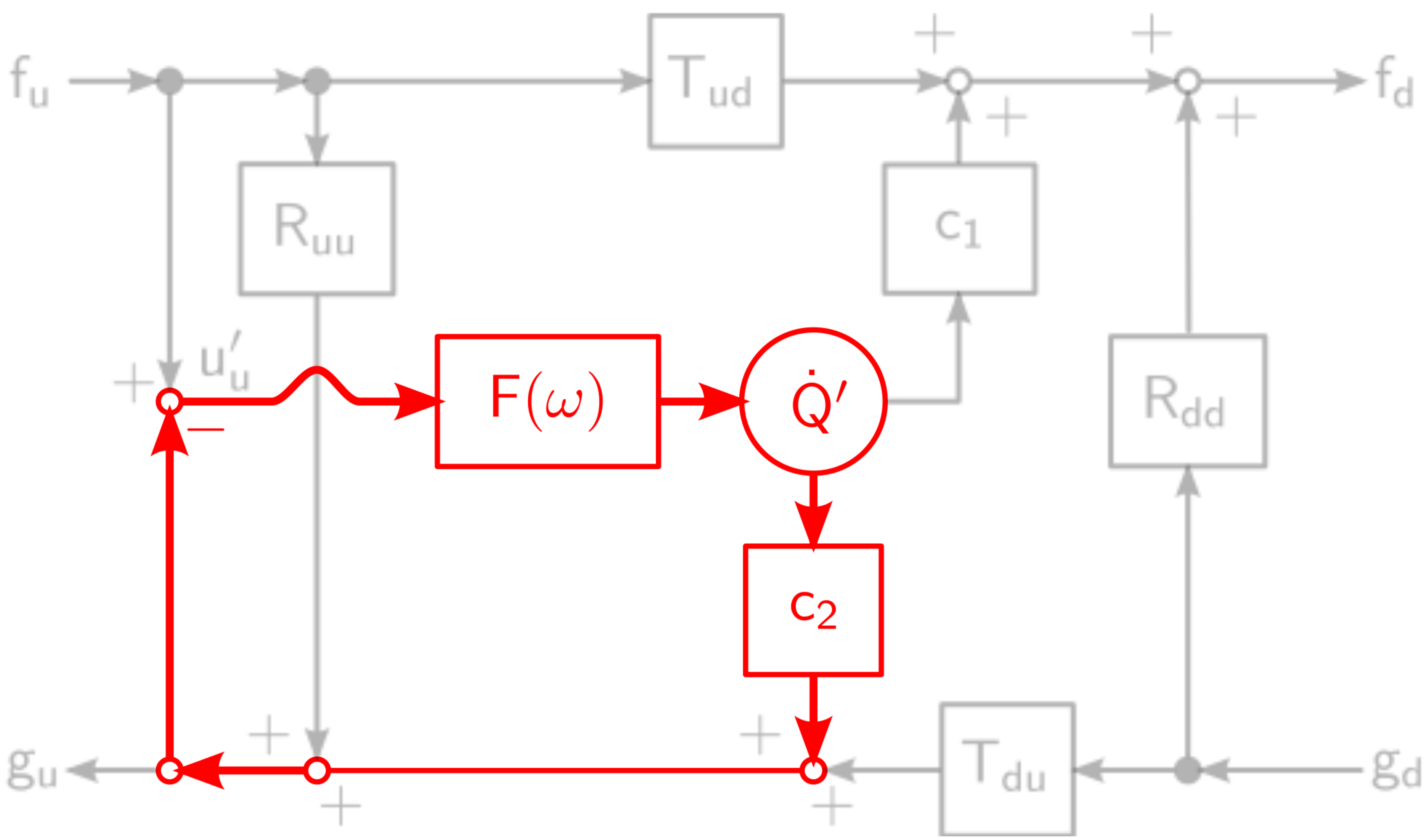

Thanks

Alp Albayrak, Sebastian Bomberg, Thomas Emmert, Guillaume Fournier, Alexander Gentemann, Matthias Häringer, Stefan Jaensch, Thomas Komarek, Malte Merk, Felicitas Schäfer, Thomas Steinbacher, Gary Yong

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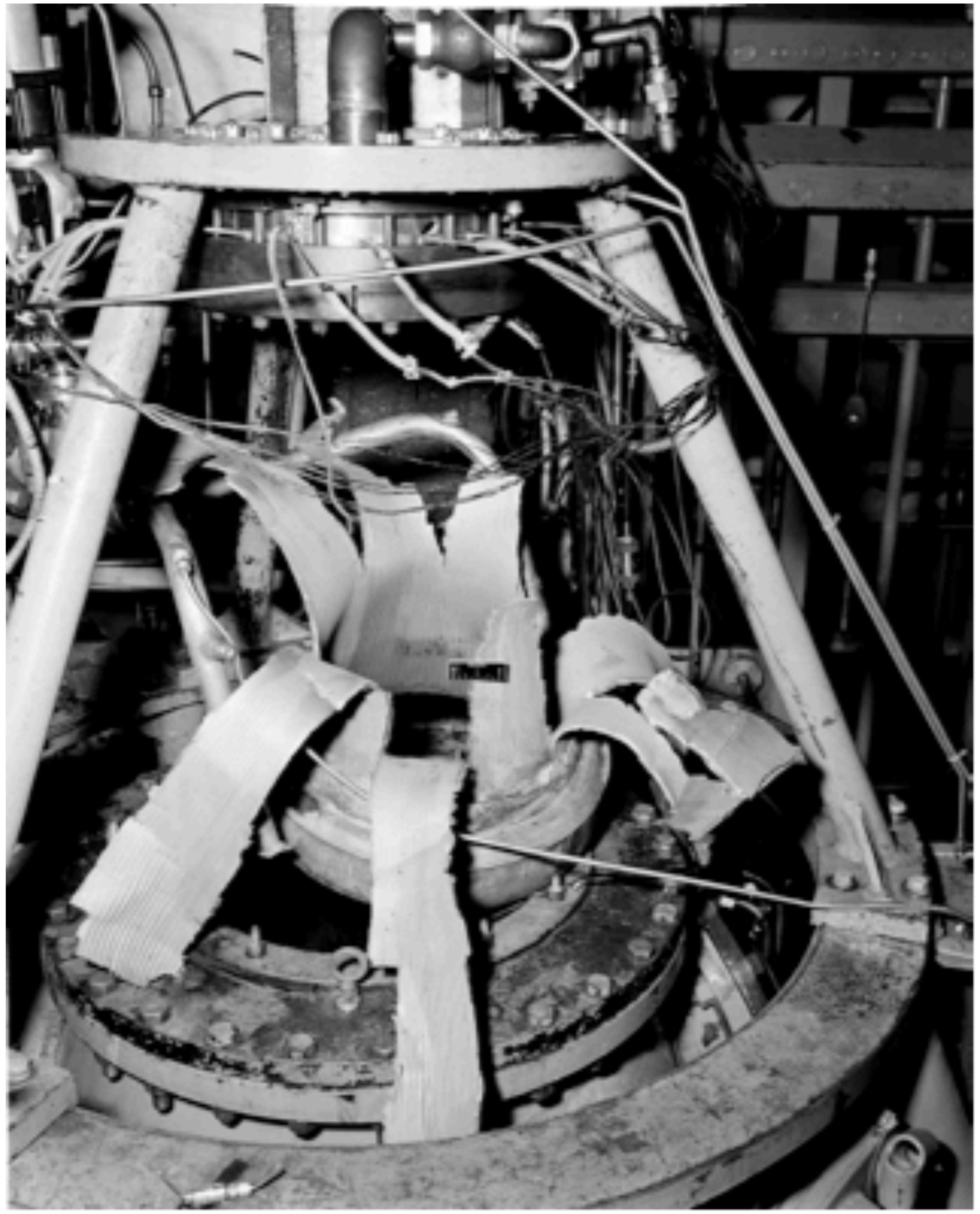
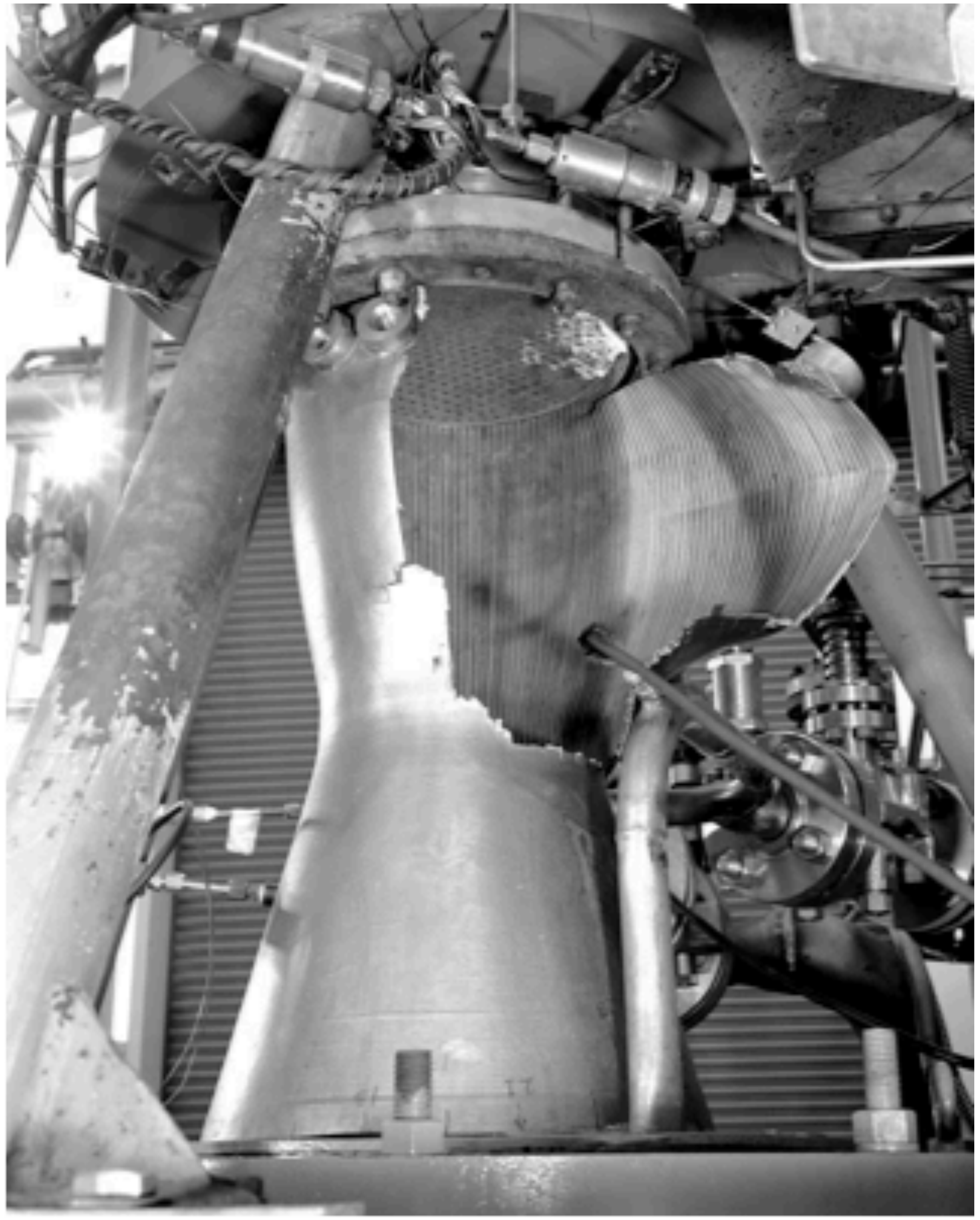
Thermoacoustic instabilities are a major challenge for combustion technology

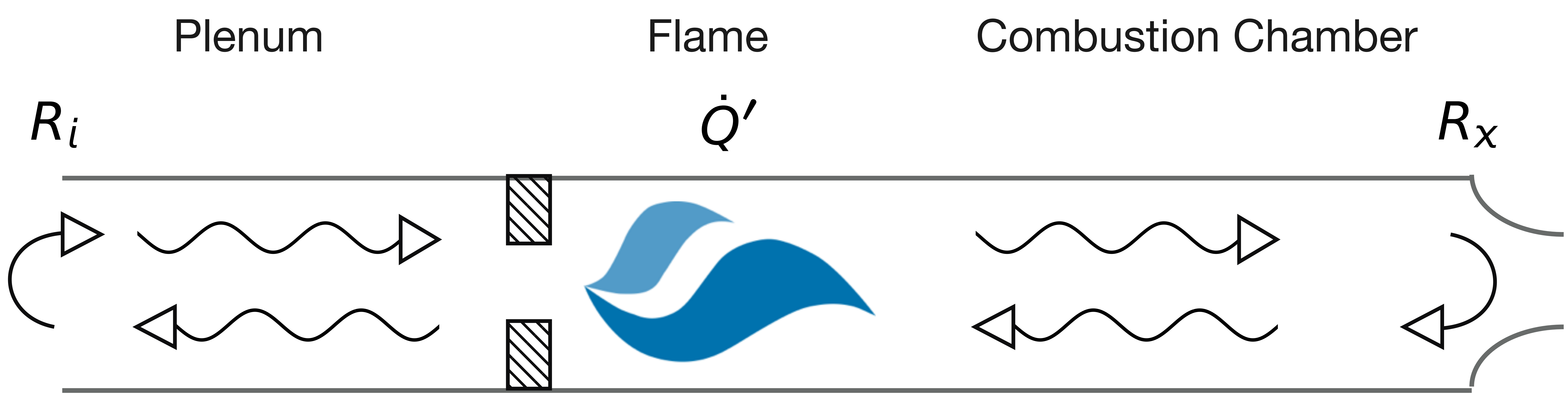


Liquid rocket engine (NASA 1957)



Liquid rocket engine (NASA 1963)

The established paradigm of thermoacoustic instability:
Unsteady flame heat release drives one of the acoustic cavity modes



A fluctuating flame is a monopole source of sound ➔ combustion noise or instability

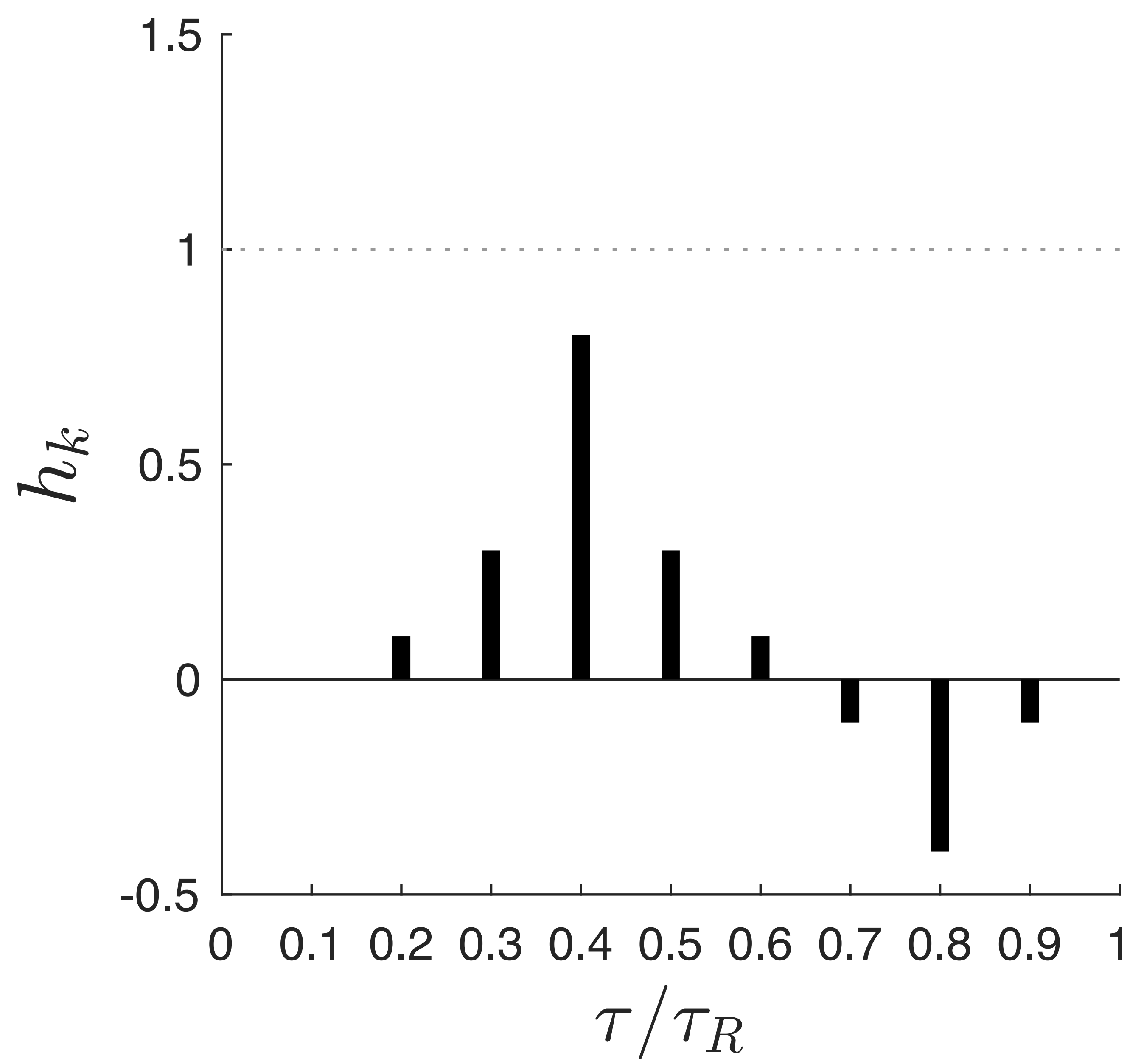
Flame heat release rate responds to fluctuations of velocity with a time lag

$$\dot{Q}'(t) \leftarrow u'(t - \tau)$$

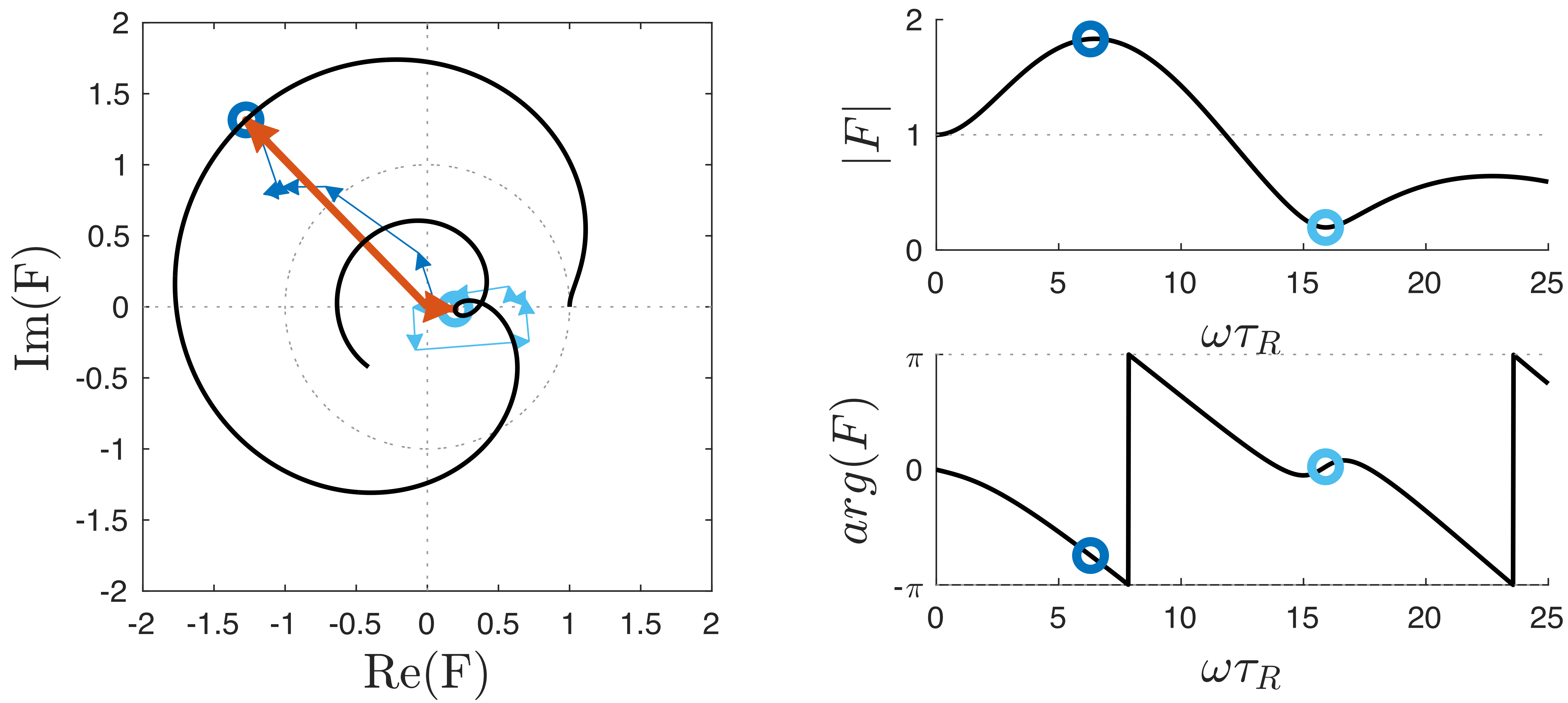
Self-excited thermo-acoustic instability may result if phases $p' \leftrightarrow \dot{Q}' \leftrightarrow u'$ are favorable

The flame impulse response $\mathbf{h}$ and the flame transfer function $\mathscr{F}$ describe how flame heat release $\dot{Q}'$ responds to velocity u'

Time Domain | Frequency Domain



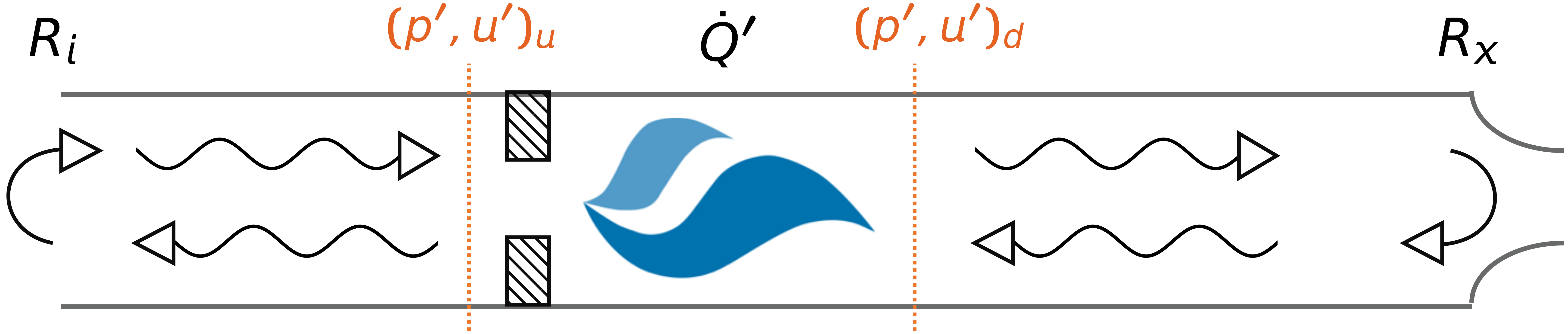
Impulse response $\mathbf{h}$



Flame Transfer Function $\mathscr{F}$ (FTF)

Polifke, PECS 2020

The transfer matrix $\hat{T}$ of burner & flame links the flame transfer function $\mathscr{F}$ to up- and downstream acoustic variables u', p'



$$\begin{pmatrix} \frac{p'}{\rho c} \\ u' \end{pmatrix}_d = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} \frac{p'}{\rho c} \\ u' \end{pmatrix}_u$$

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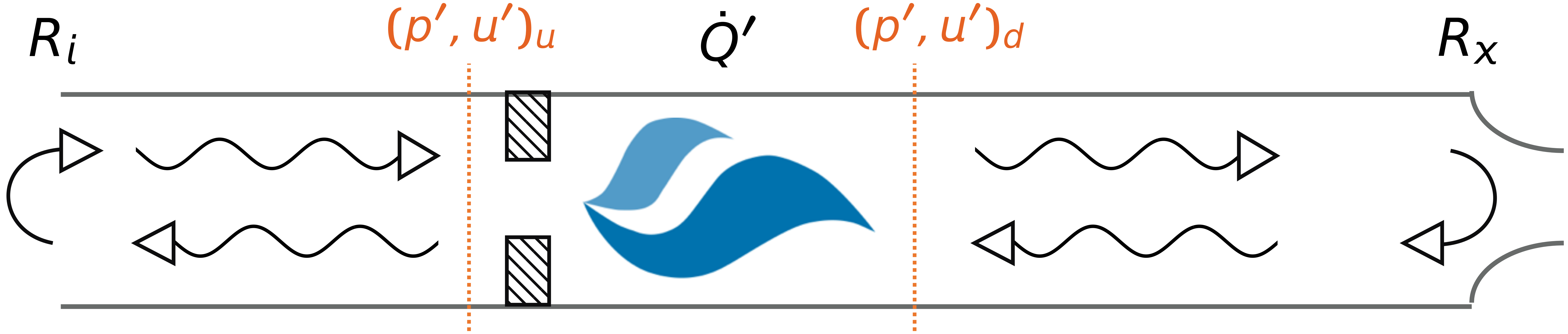

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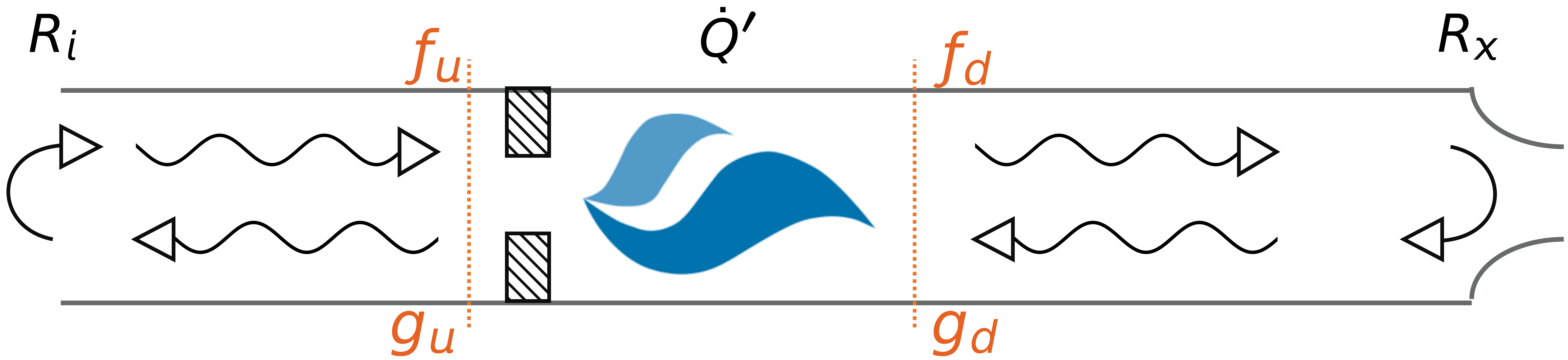
$$\begin{pmatrix} \frac{\rho_c c_c}{\rho_h c_h} & -\zeta M + i\frac{\omega l_{\mathrm{red}}}{c_c} \\ 0 & 1 + \left(\frac{T_h}{T_c} - 1\right)\mathcal{F}(\omega) \end{pmatrix}$$

The scattering matrix $\hat{S}$ provides an alternative description in terms of reflection and transmission coefficients for the characteristic wave f, g



$$\begin{pmatrix} f_d \\ g_u \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} f_u \\ g_d \end{pmatrix}$$

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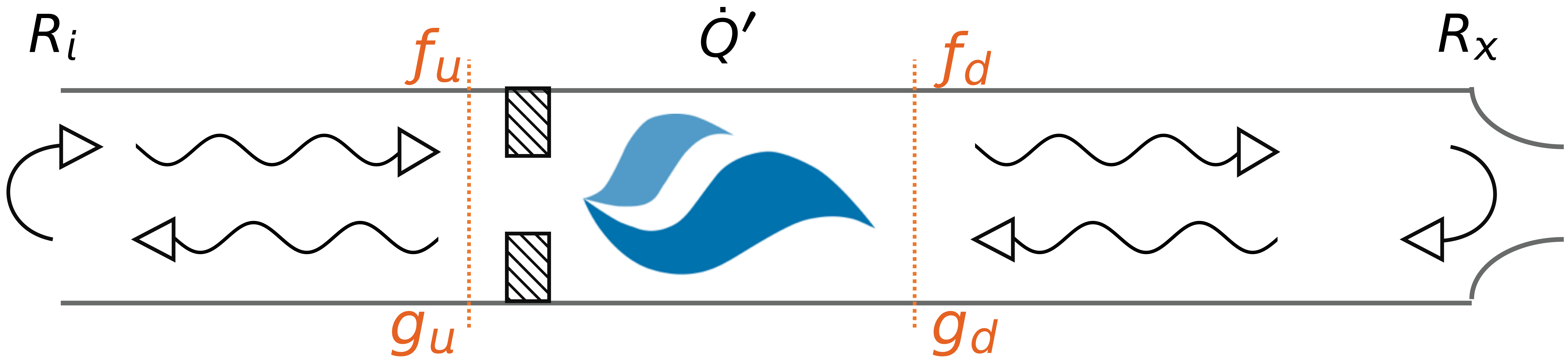

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$$\begin{pmatrix} t_u & r_d \\ r_u & t_u \end{pmatrix}$$

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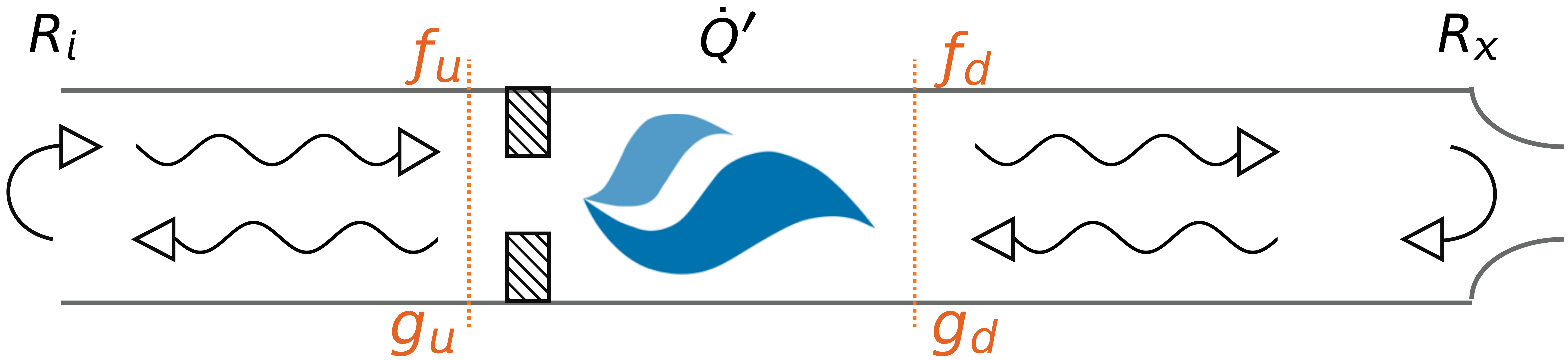

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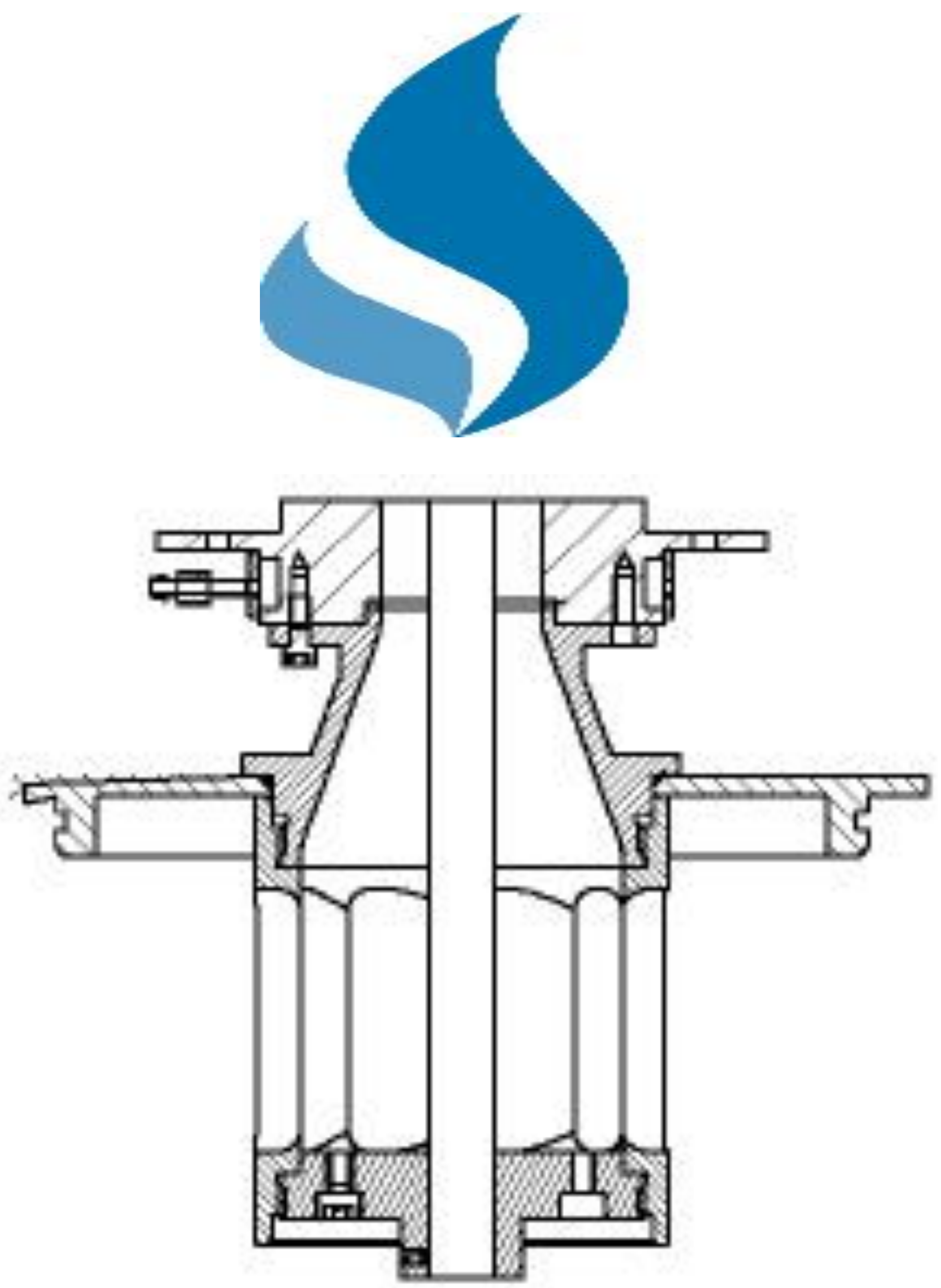
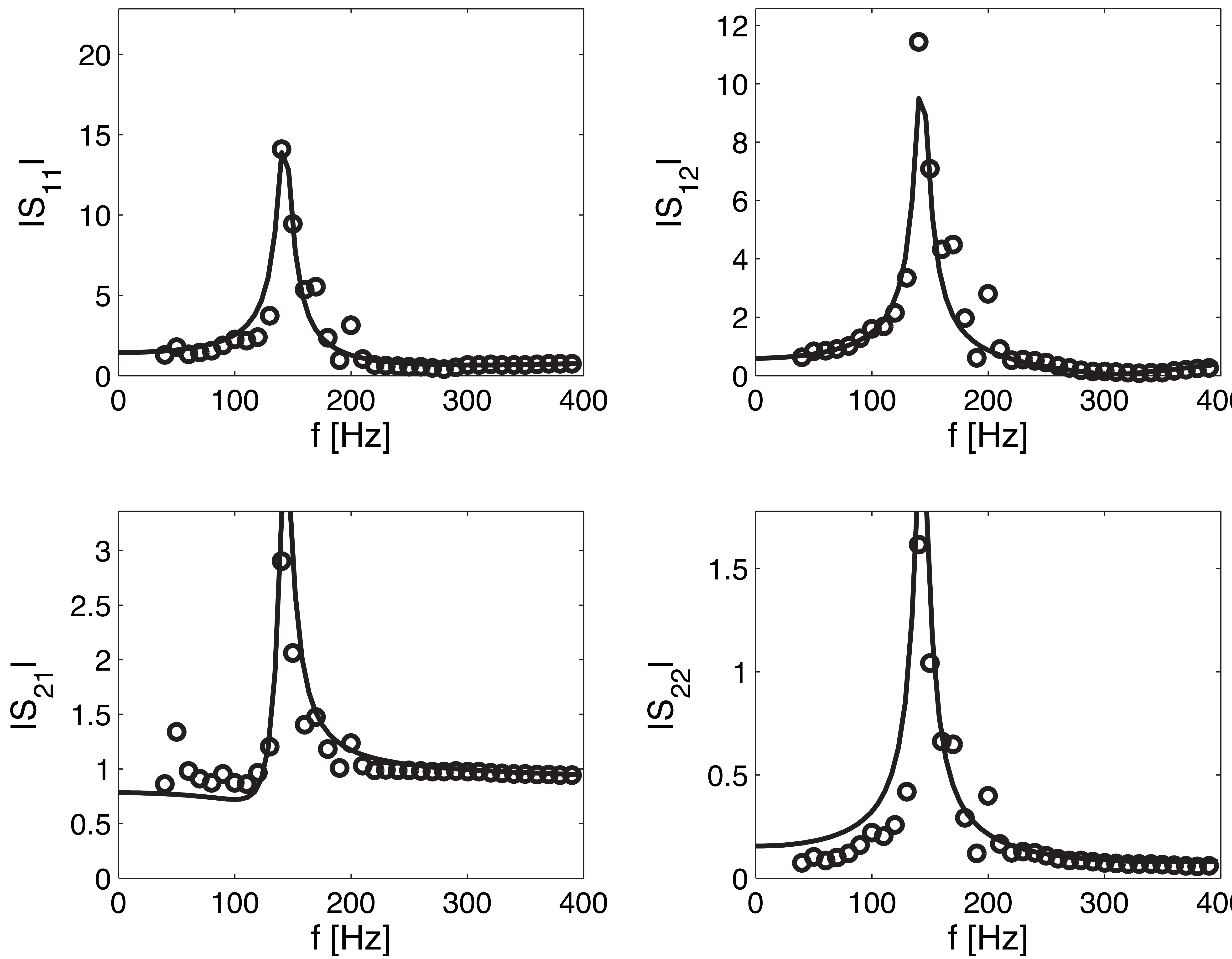
outgoing *response*

incoming *signal*

$$\begin{pmatrix} t_u & r_d \\ r_u & t_u \end{pmatrix}$$

Scattering matrix and instability potentiality of a premixed swirl burner show inexplicable peaks





Kunze, 2004, Fischer 2004, Gentemann & Polifke, ASME 2007; Polifke, ECM 2011

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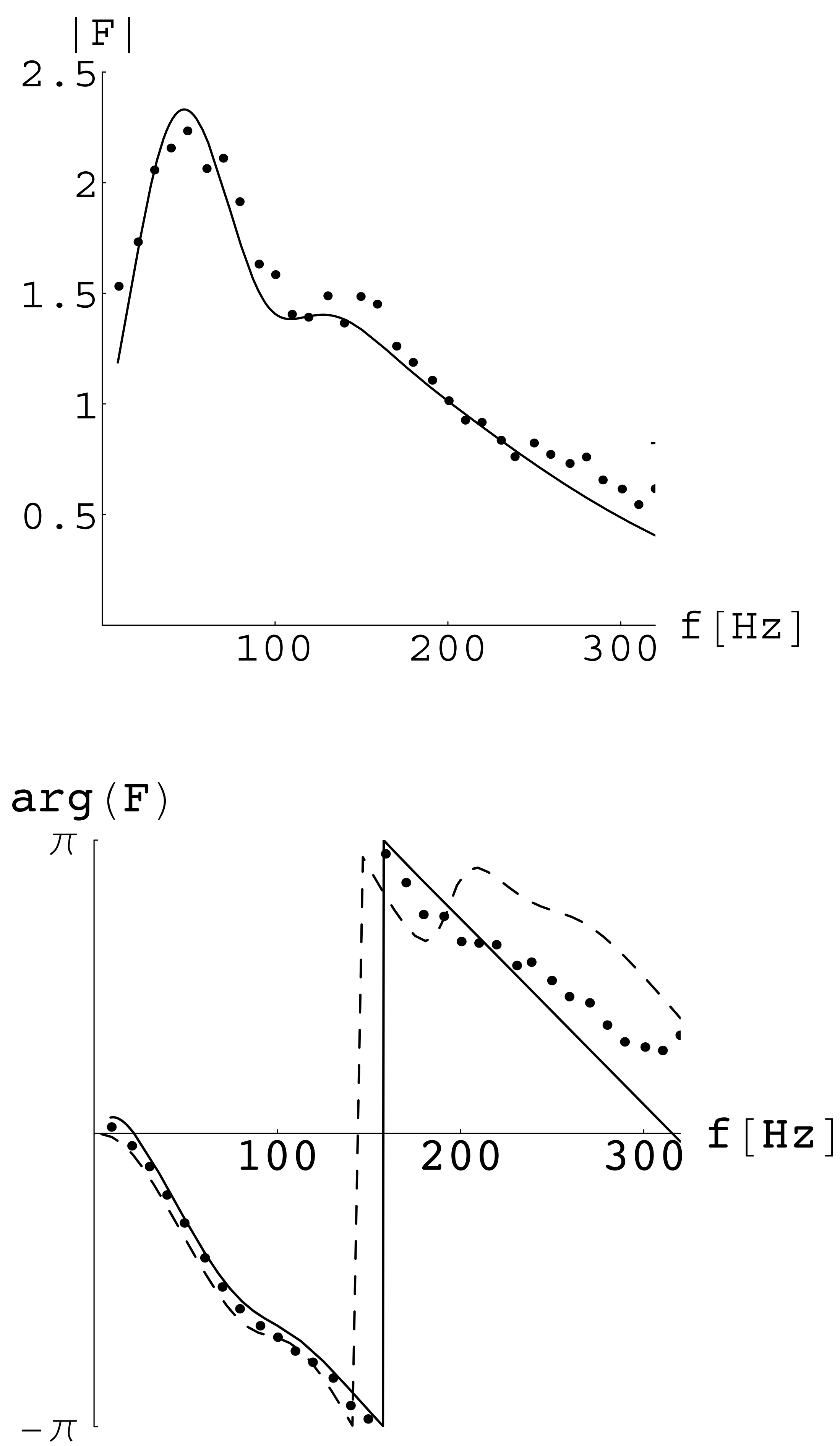

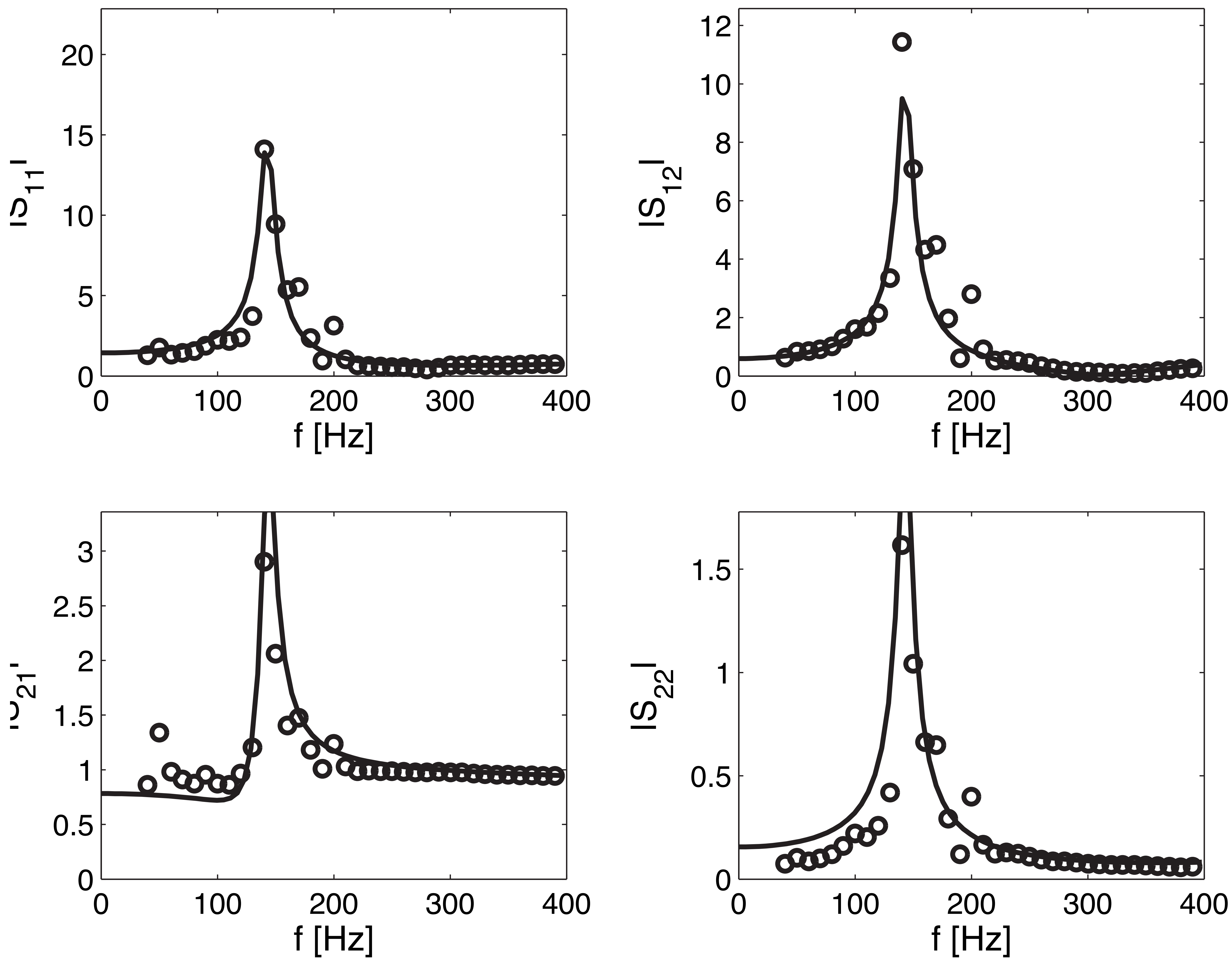

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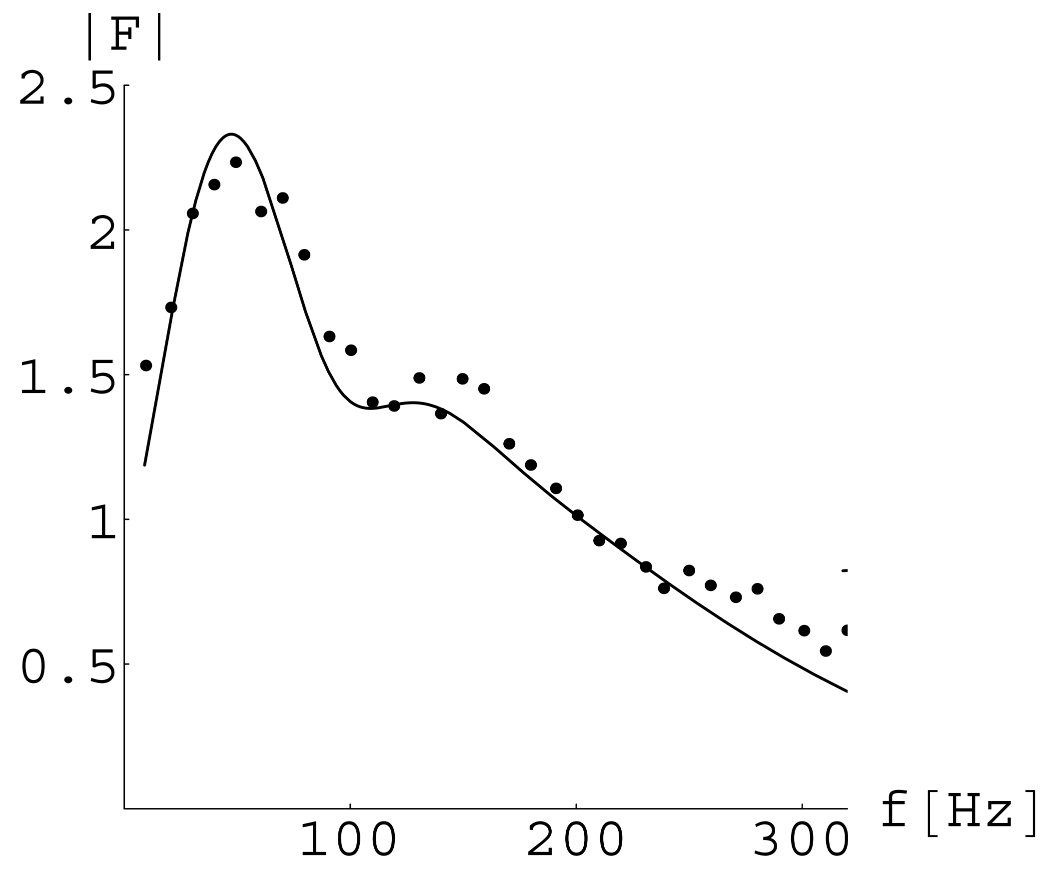

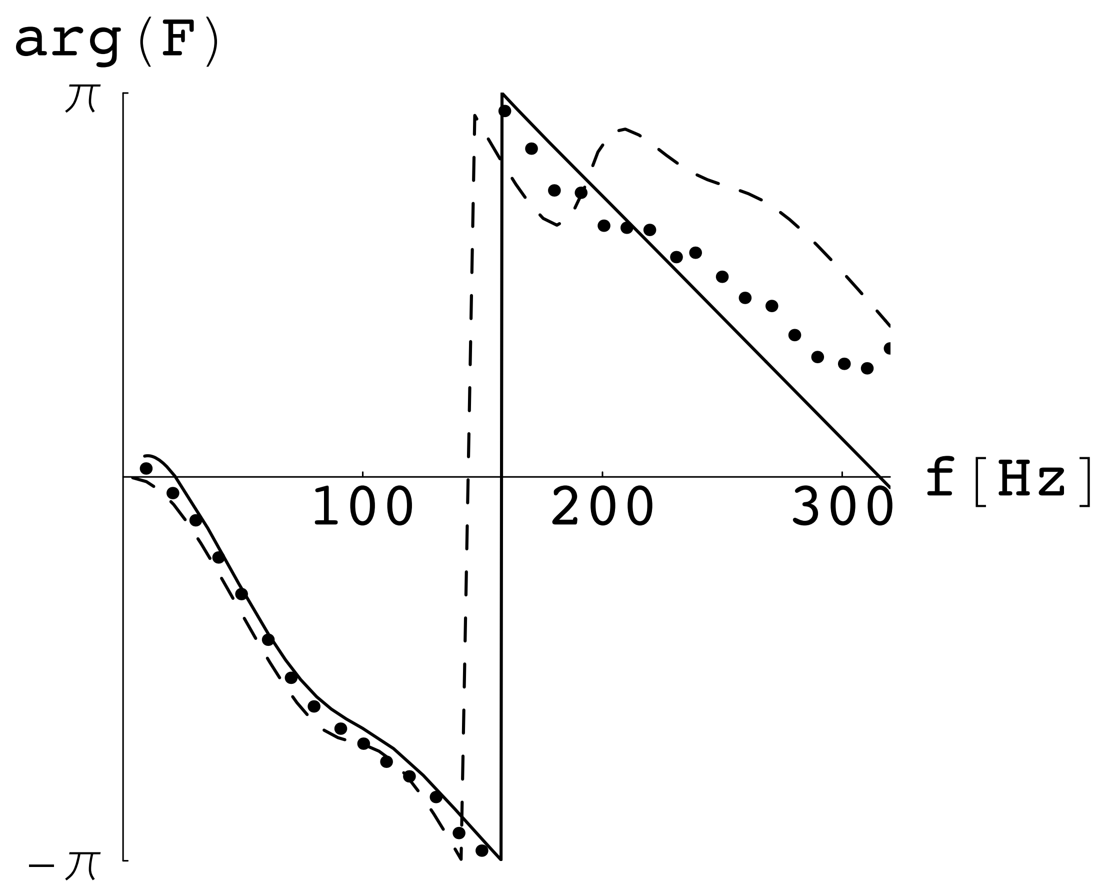

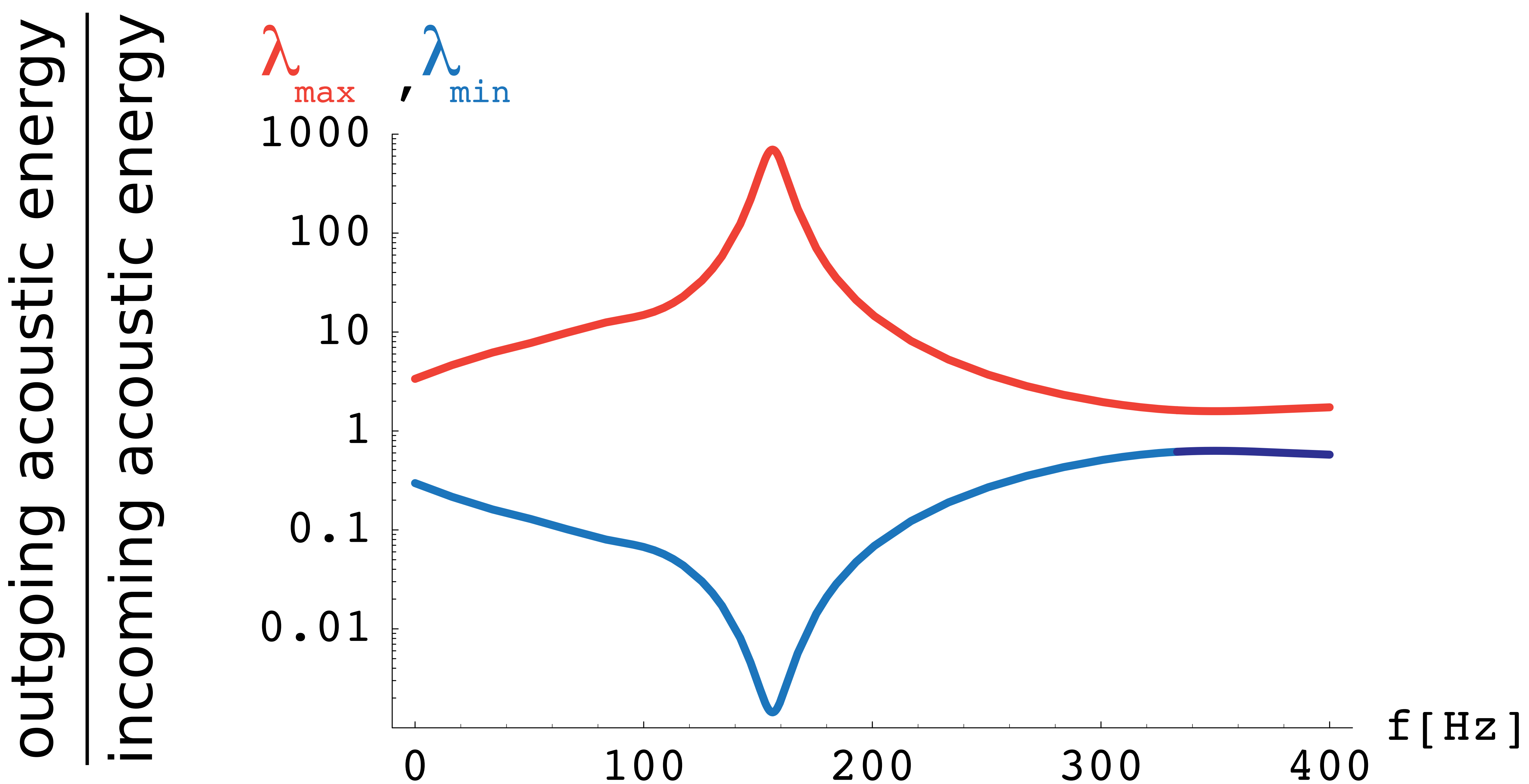

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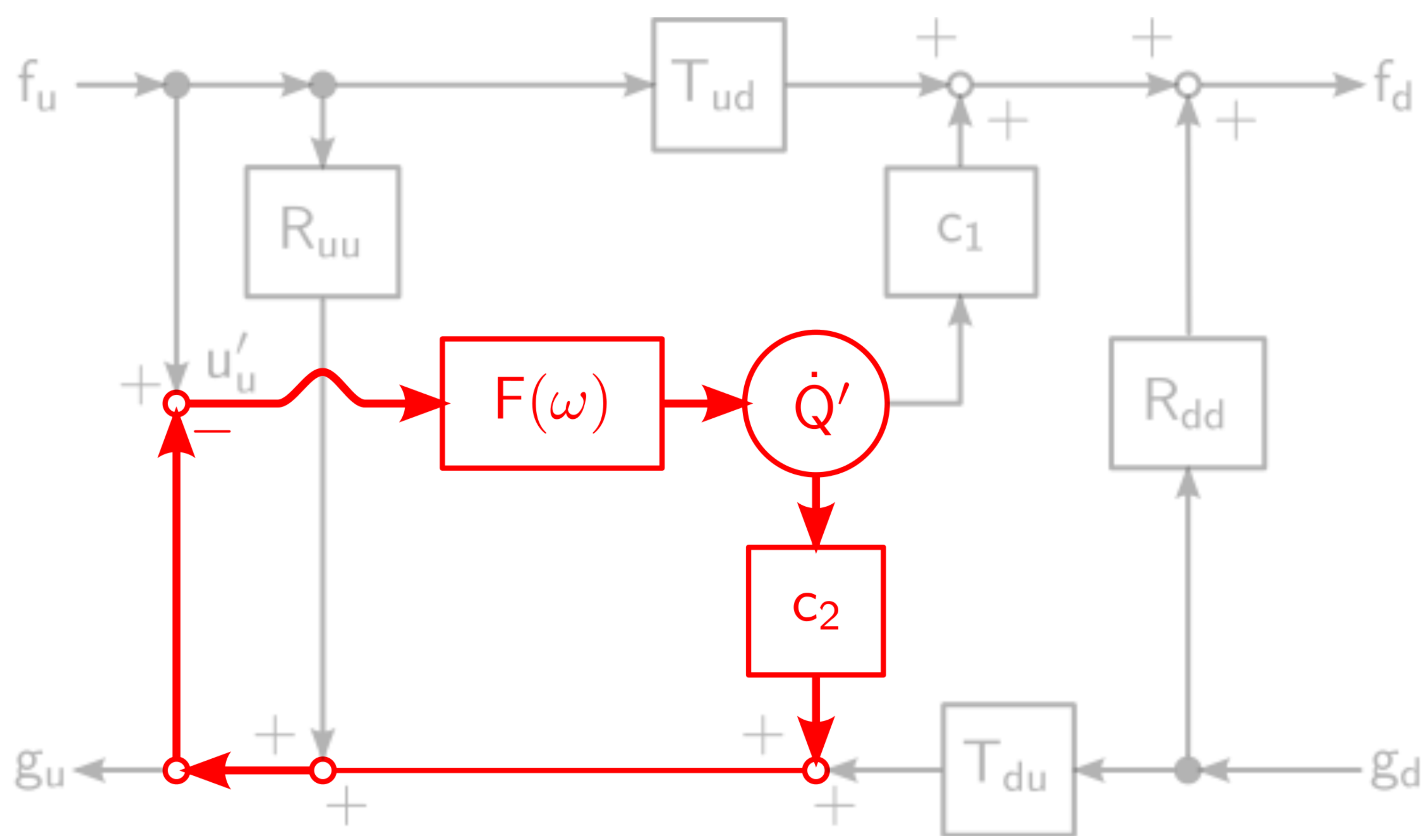
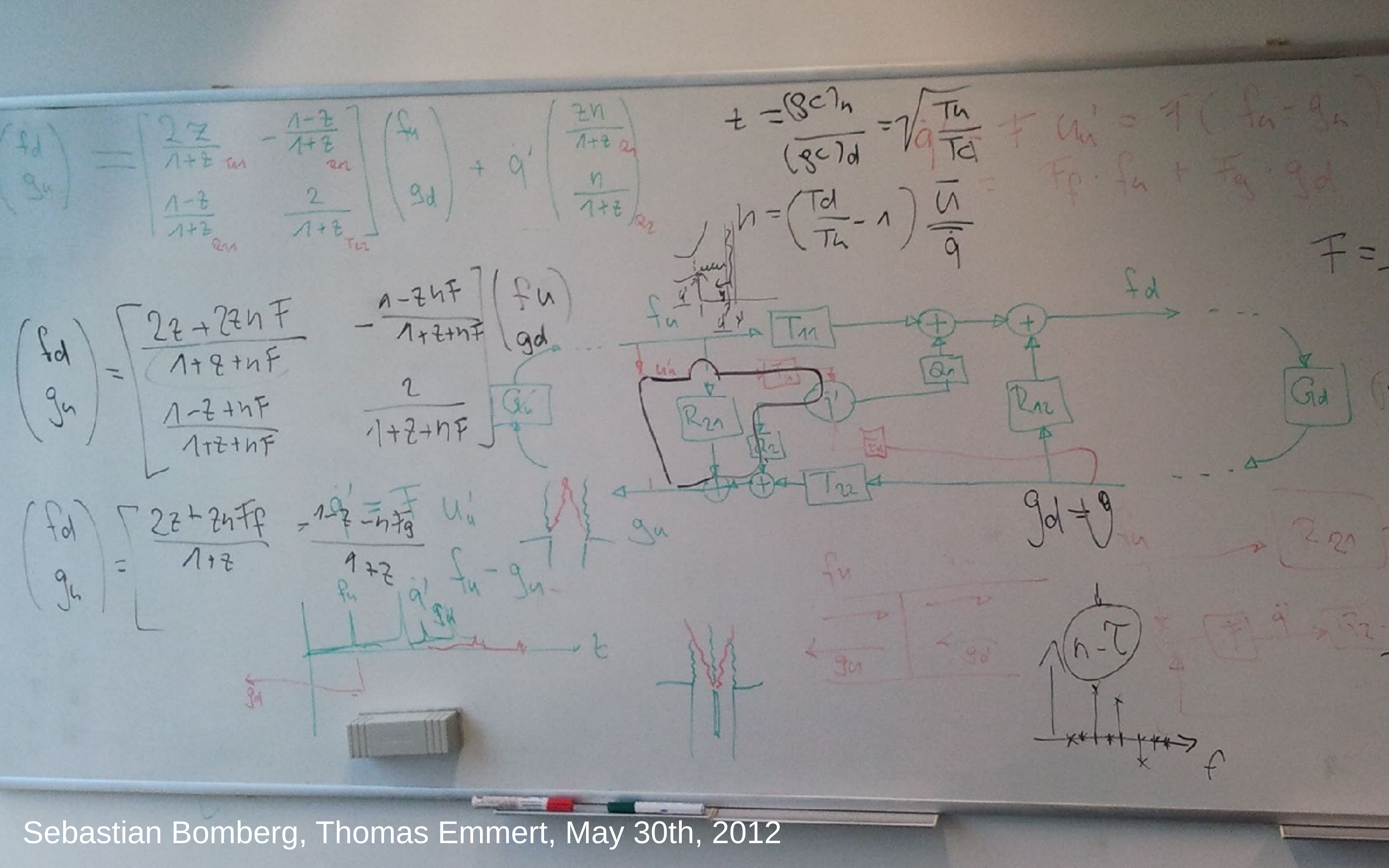
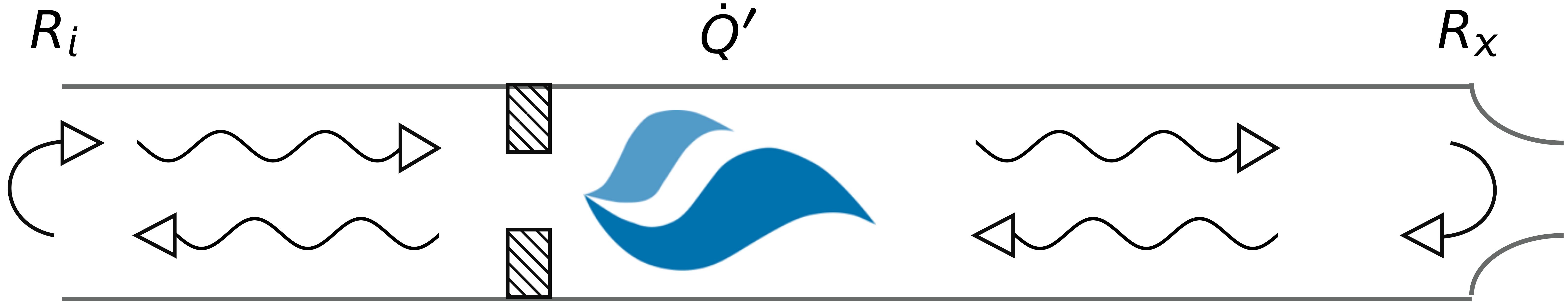
Exceptional points and clusters



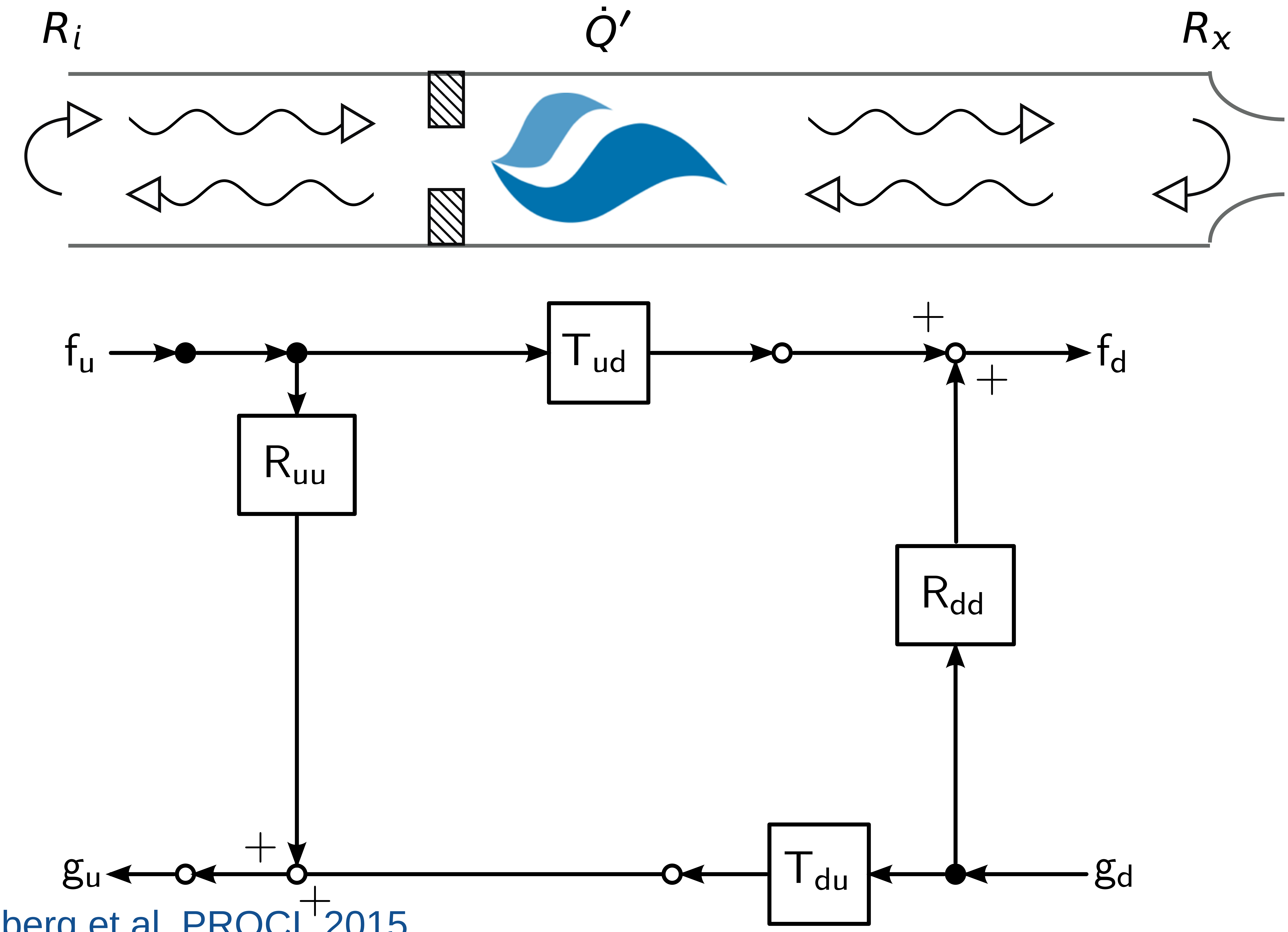


Sebastian Bomberg, Thomas Emmert, May 30th, 2012

Acoustic waves impinging upon the flame are transmitted / reflected

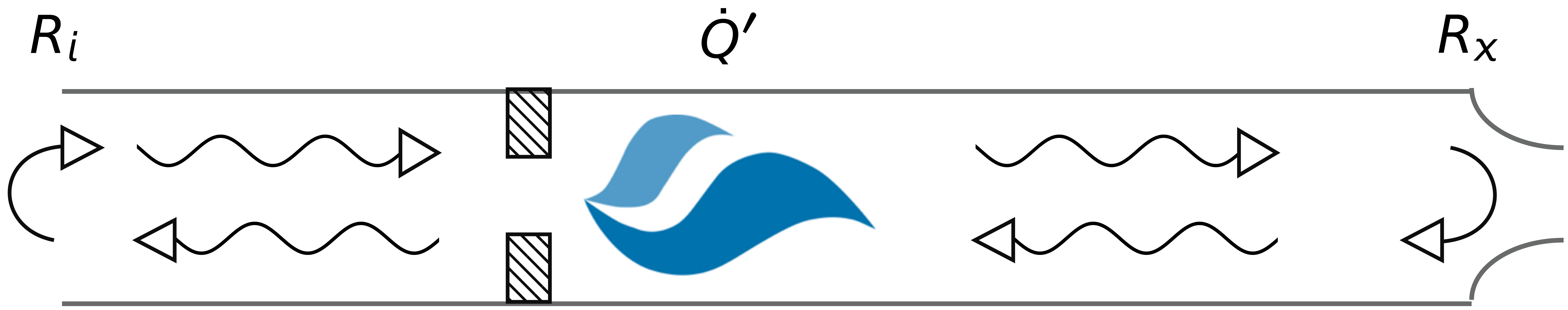


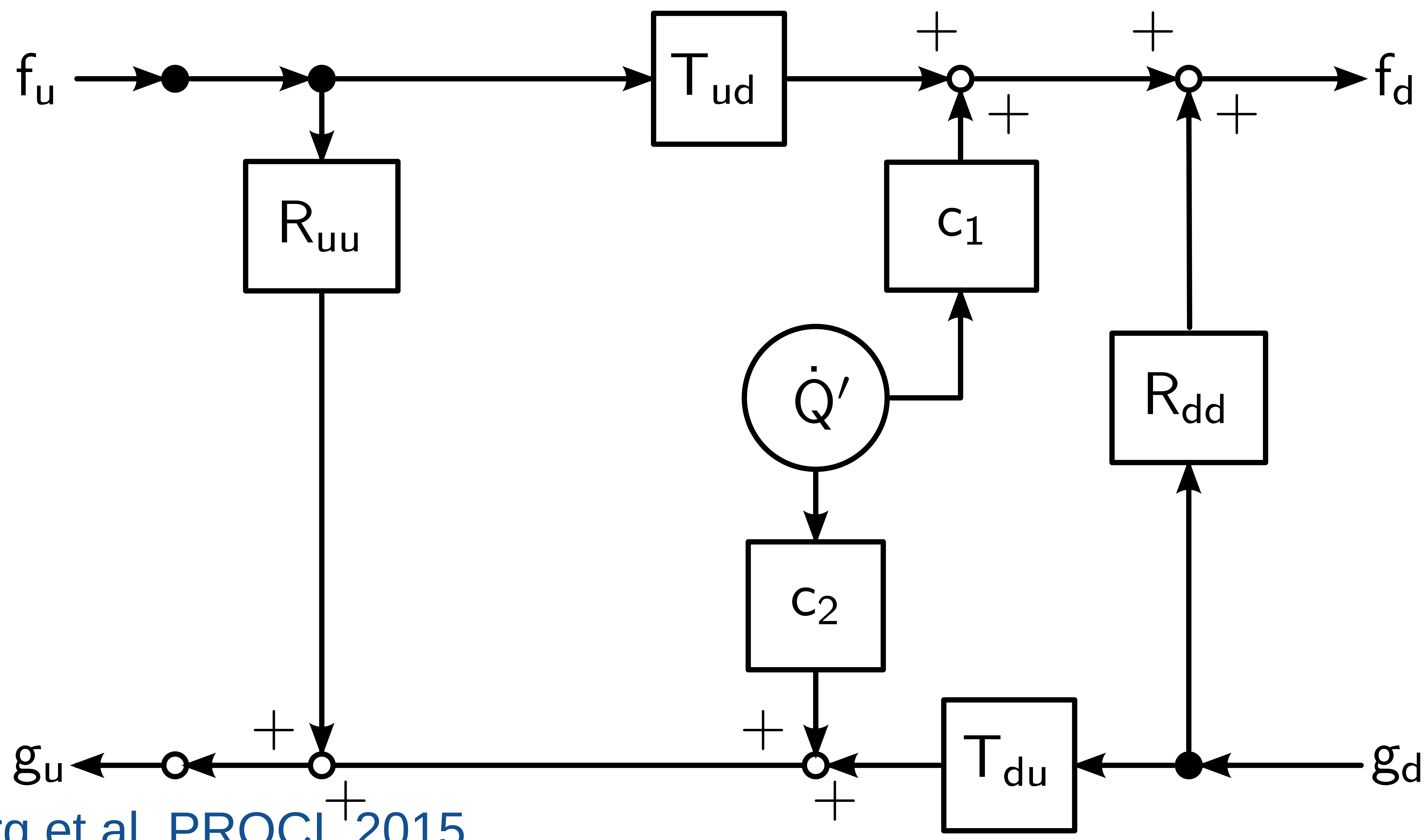
Acoustic waves impinging upon the flame are transmitted / reflected



Bomberg et al, PROCI, 2015

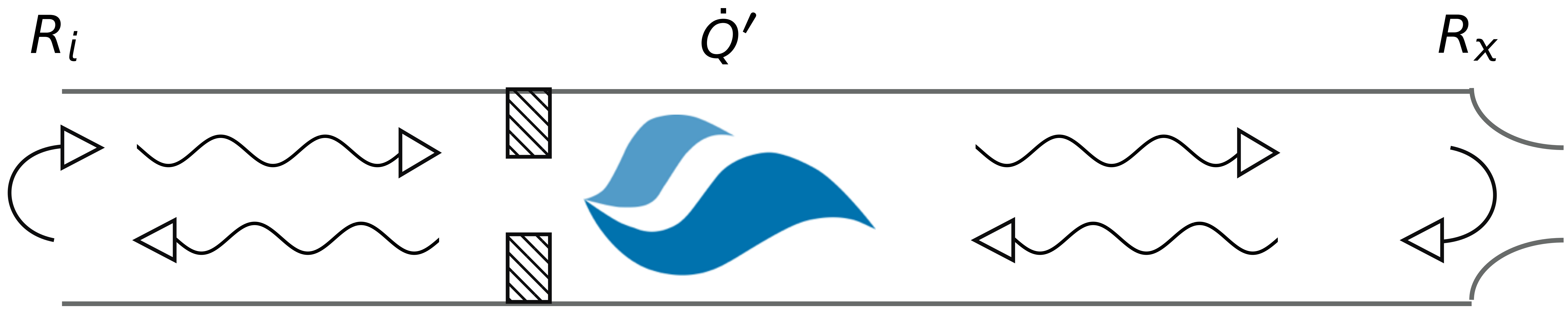
Unsteady heat release *Q'* contributes to the outgoing acoustic waves

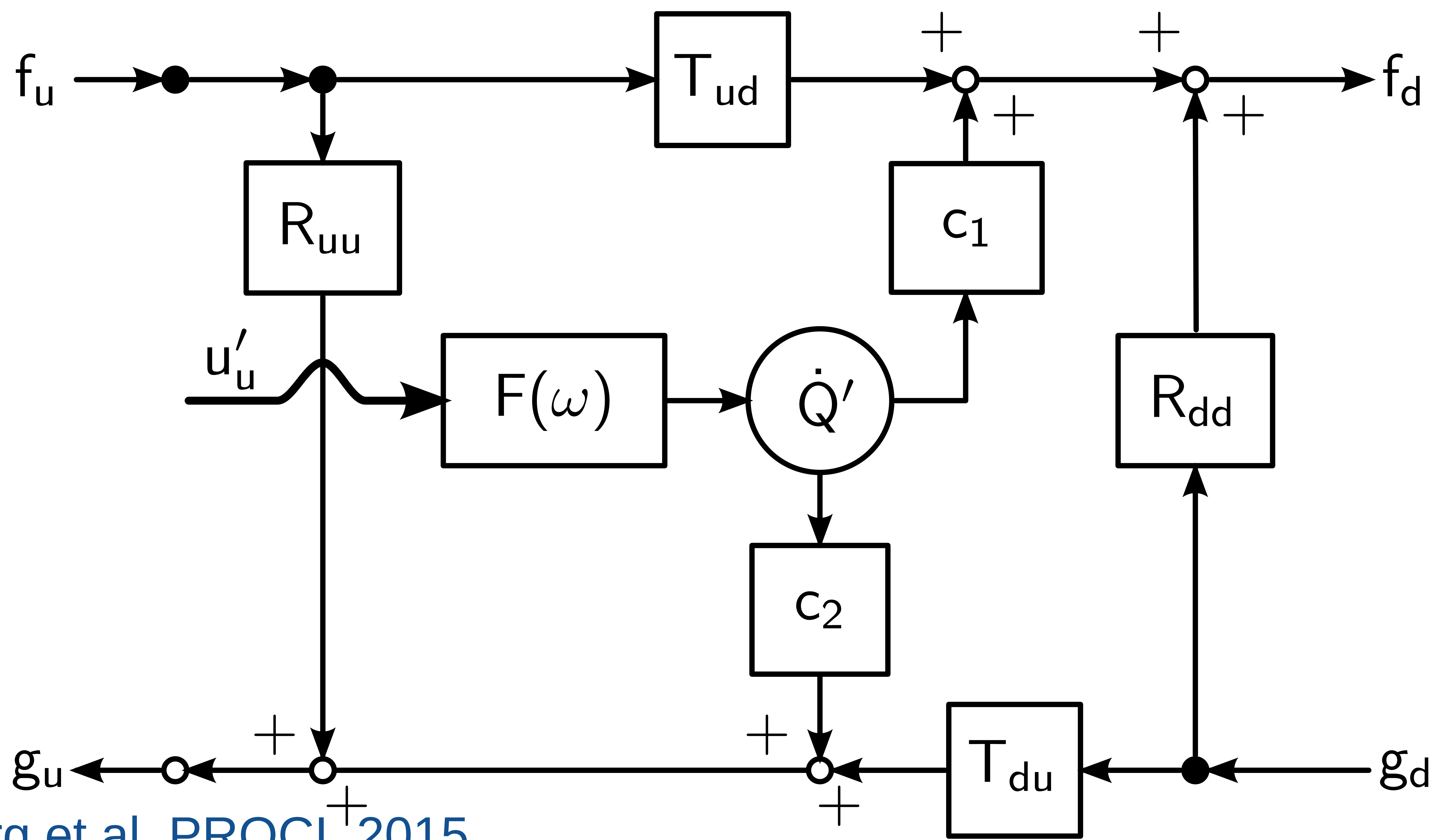




Bomberg et al, PROCI, 2015

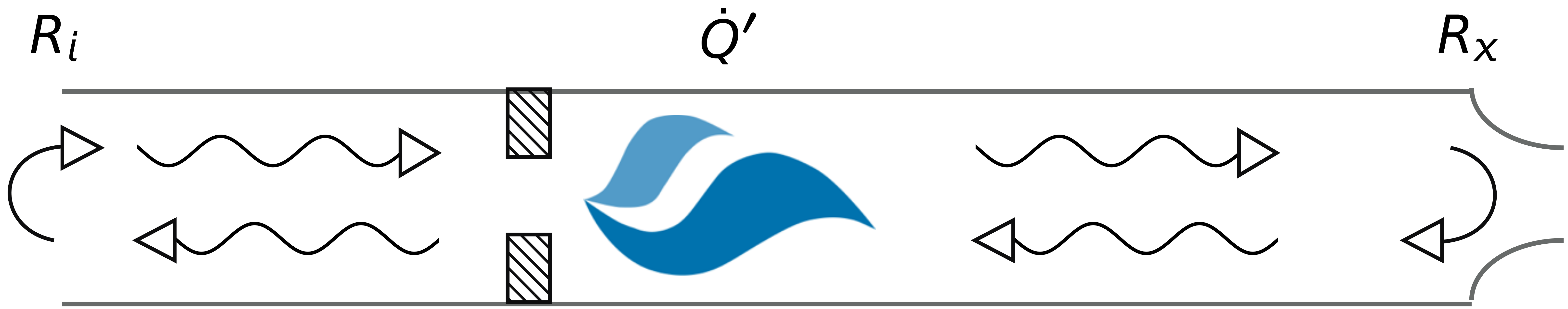
The flame heat release *Q'* is perturbed by upstream velocity u_u'

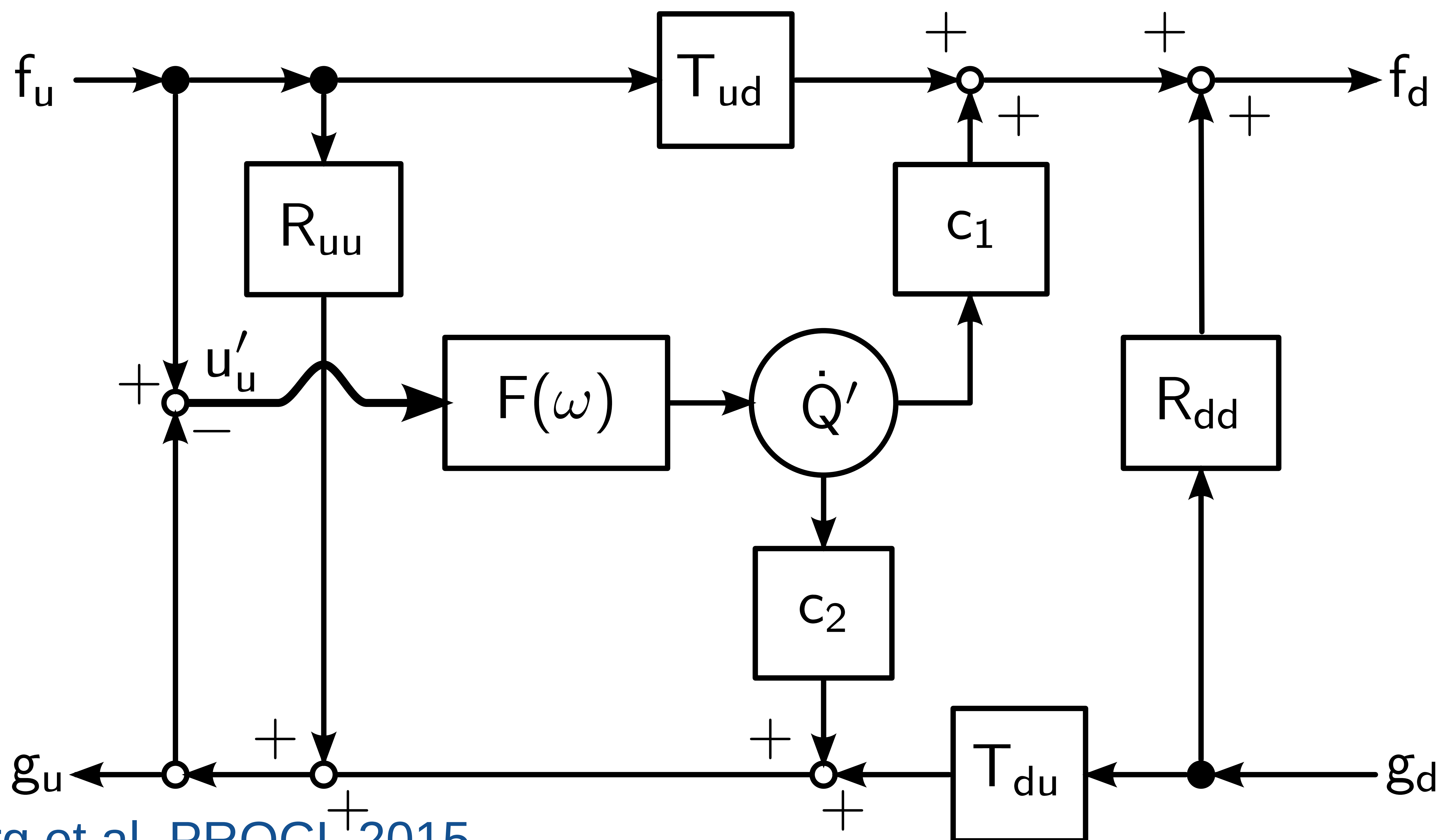




Bomberg et al, PROCI, 2015

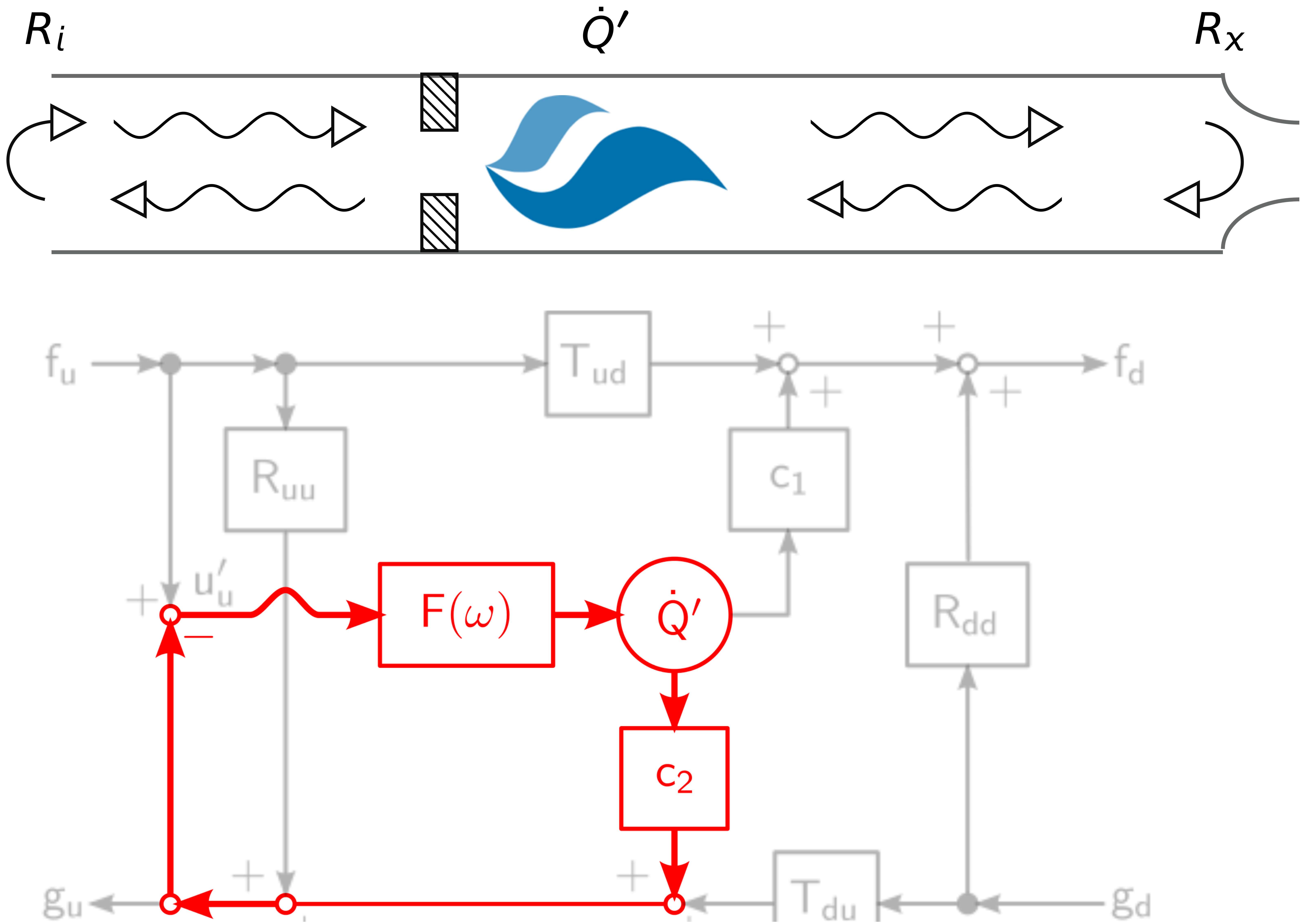
The upstream velocity u_u' is controlled by the upstream acoustics f_u, g_u





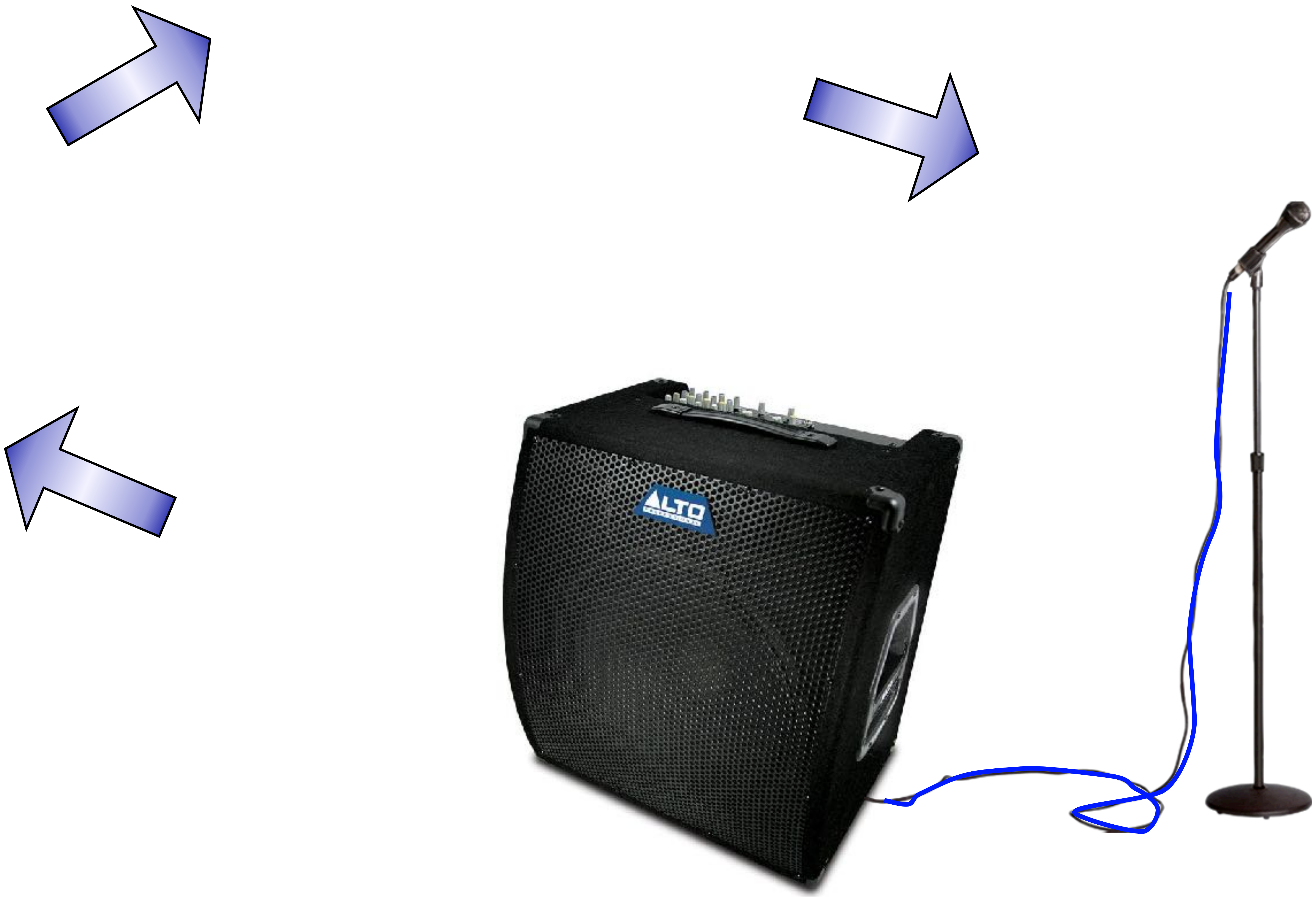
Bomberg et al, PROCI, 2015

Acoustic waves generated by unsteady heat release *Q'* perturb the velocity *u_u'* upstream of the flame → *intrinsic thermoacoustic feedback*



Bomberg et al, PROCI, 2015

Analogy: electro-acoustic feedback



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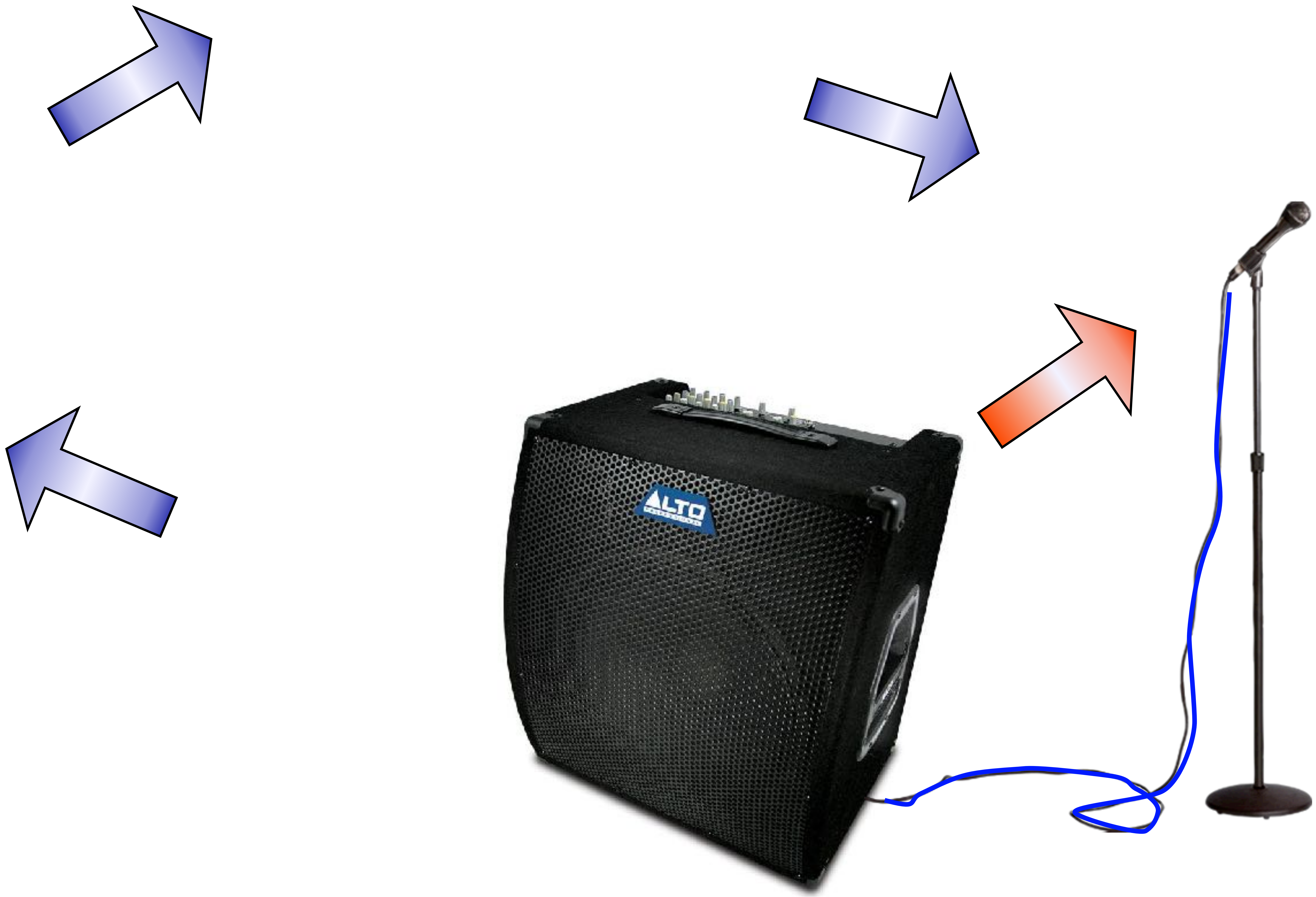
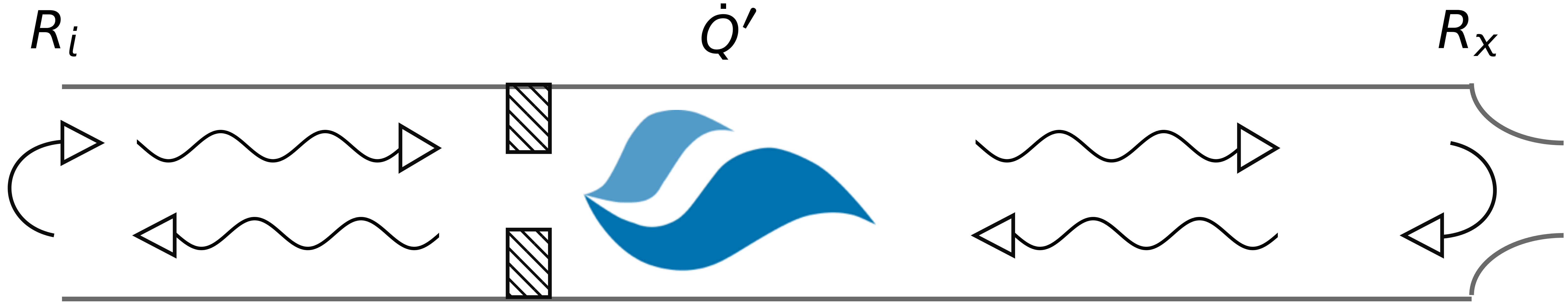
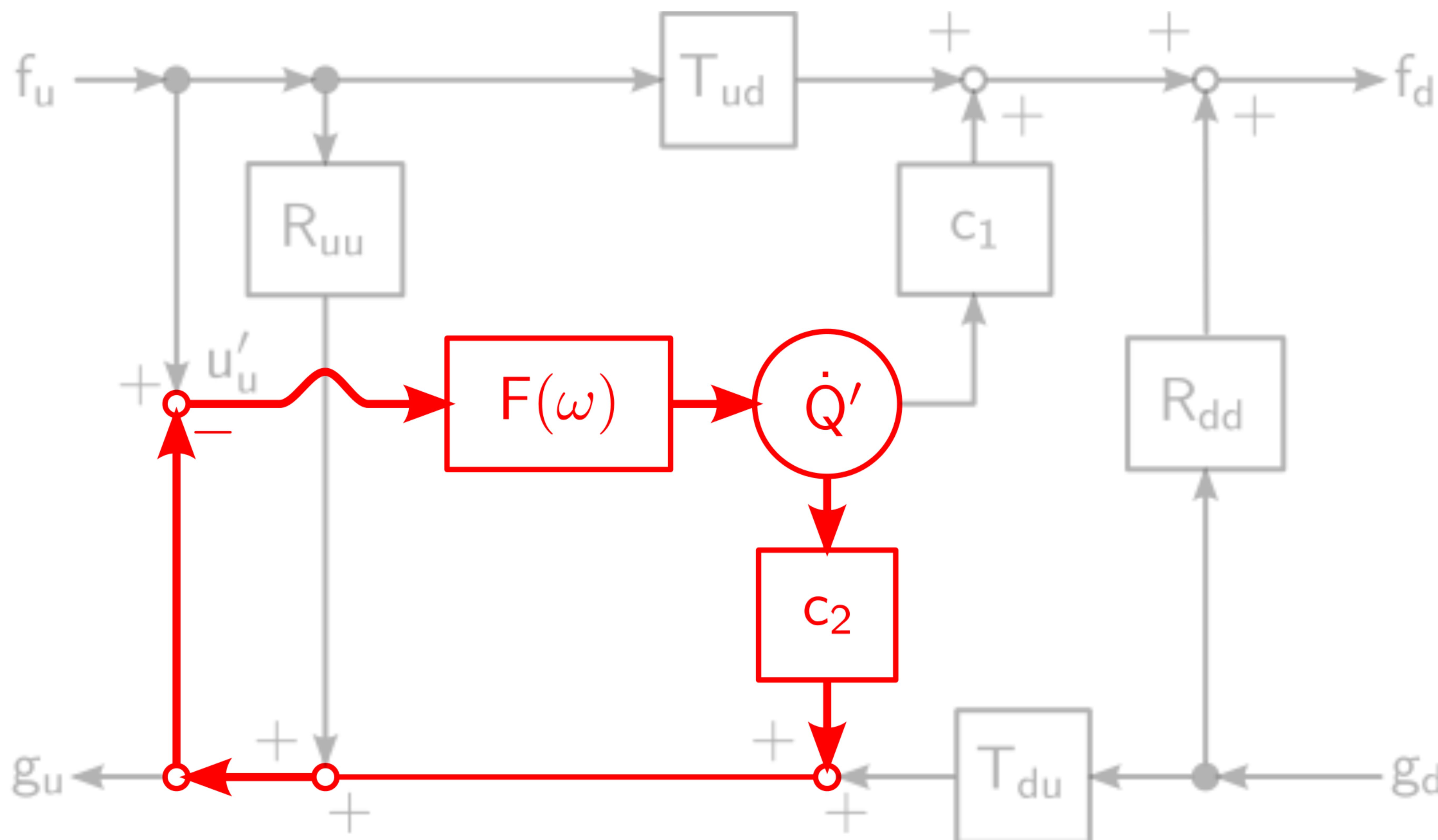


The peaks in $\hat{S}$ and the instability potentiality result from resonance with the ITA feedback loop





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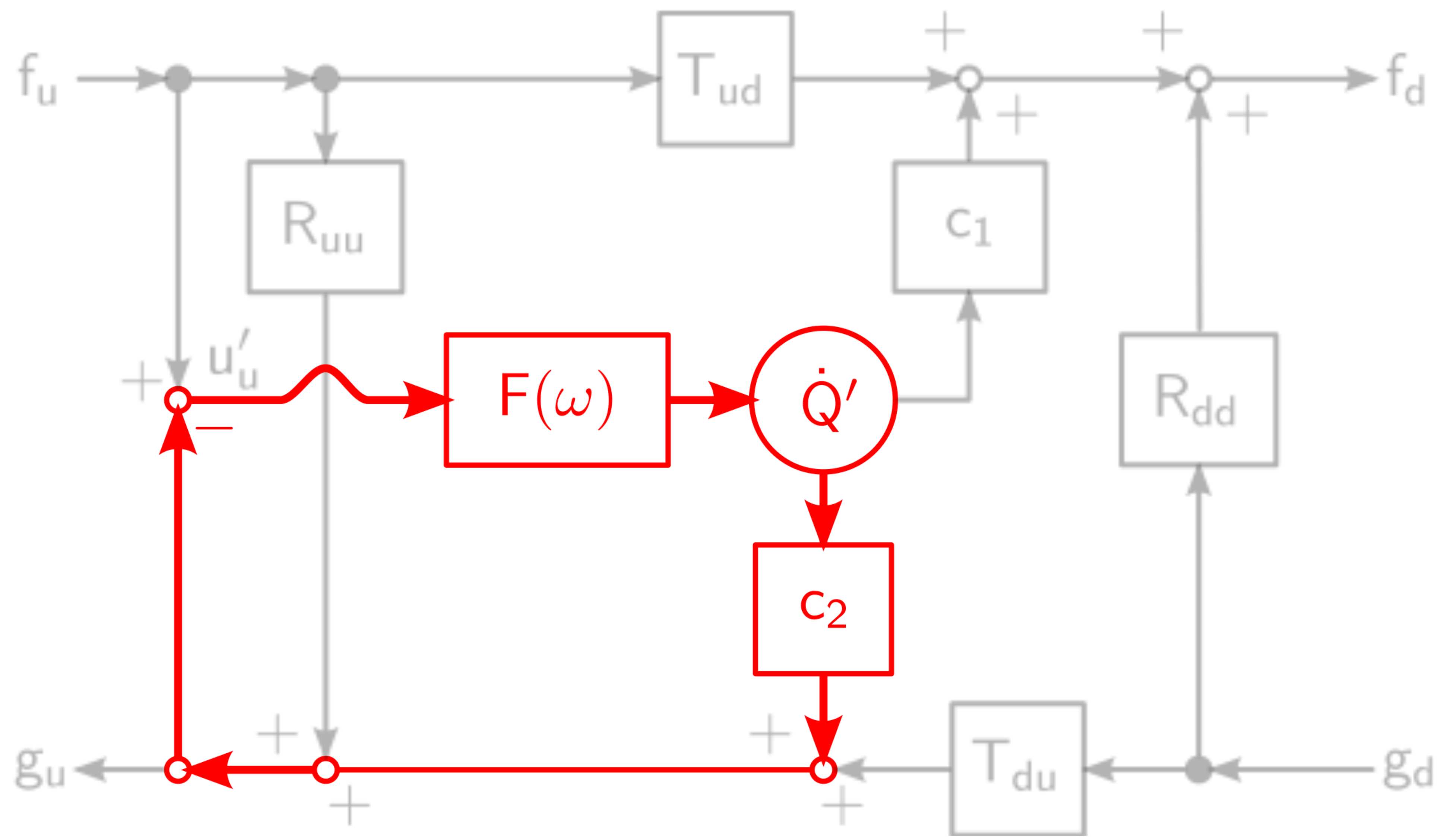
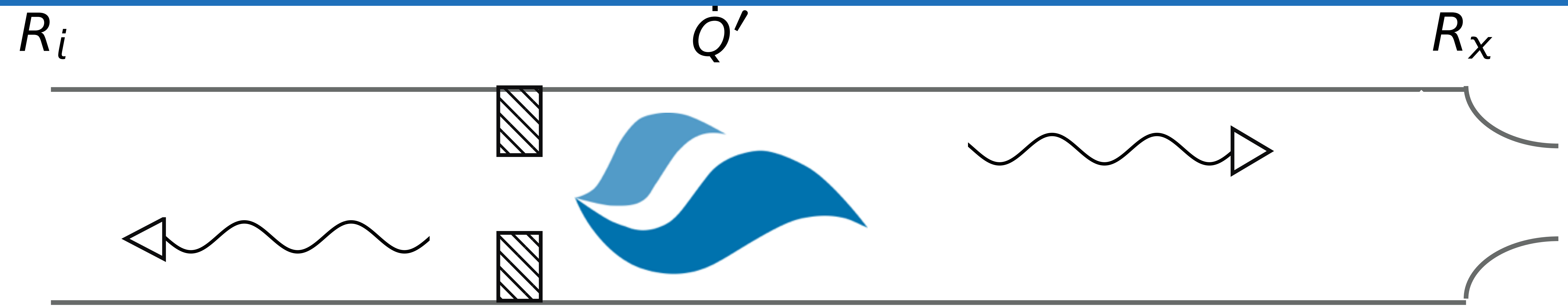


„Preventing thermo-acoustic instabilities by breaking the feedback loop" – does not work !?



Hoeijmakers et al., CNF 2014, 2016, Emmert et al, CNF, 2015

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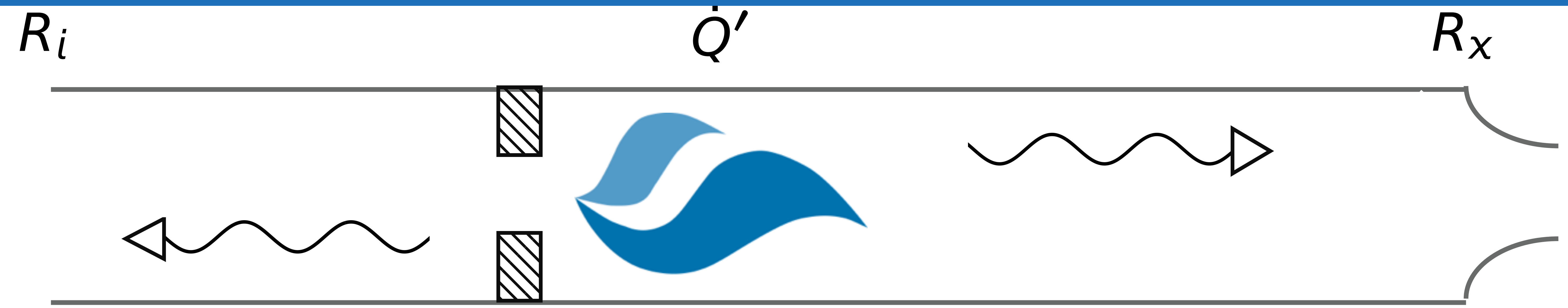

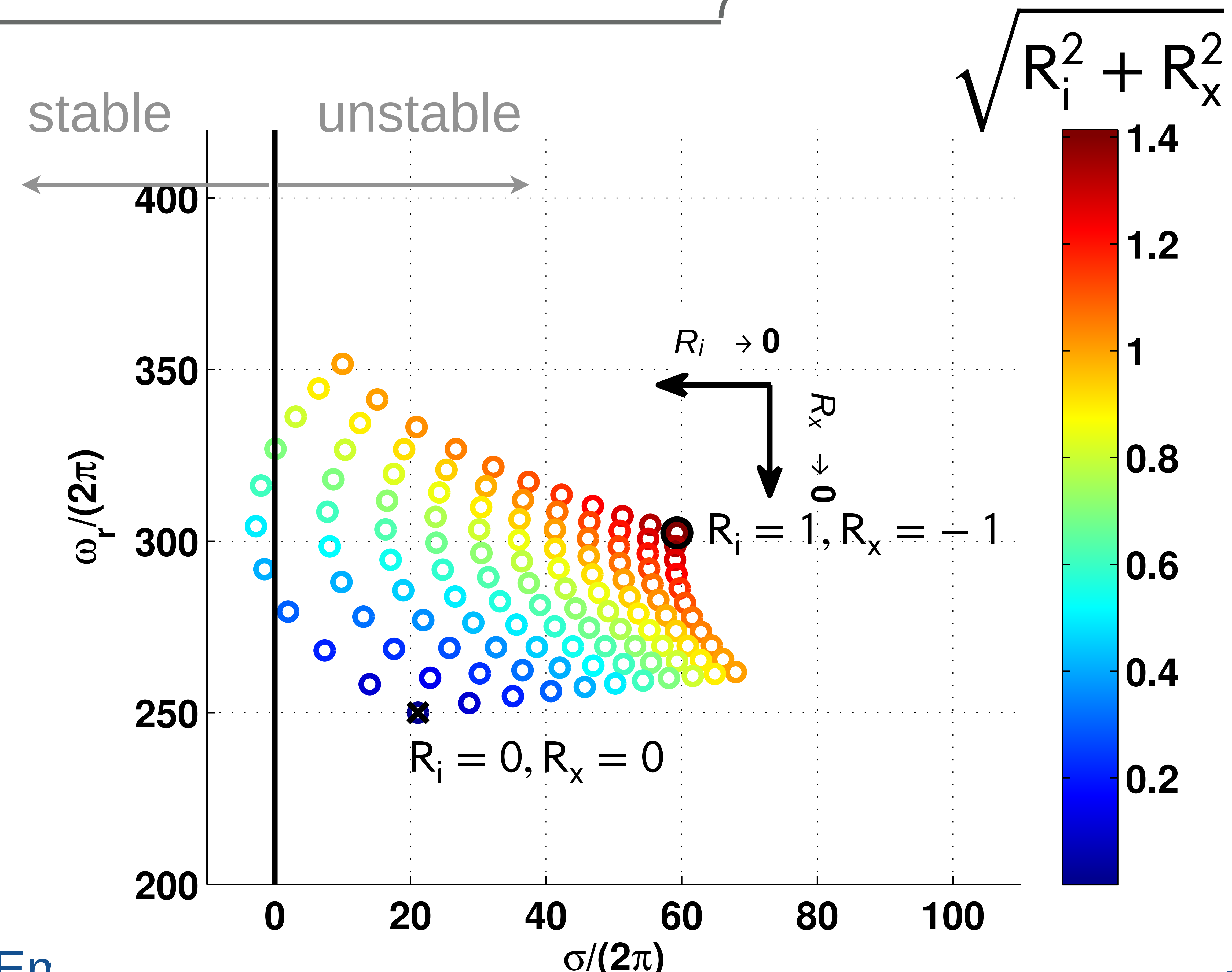

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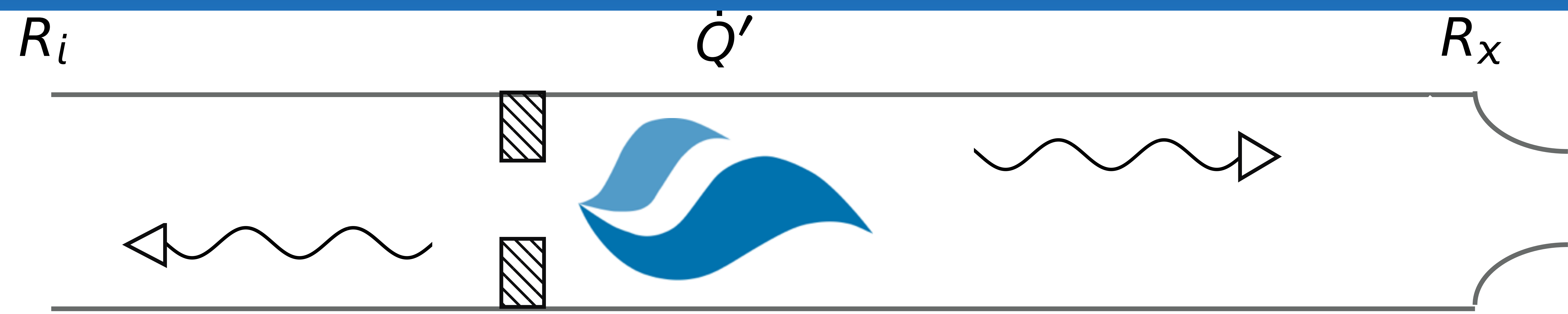
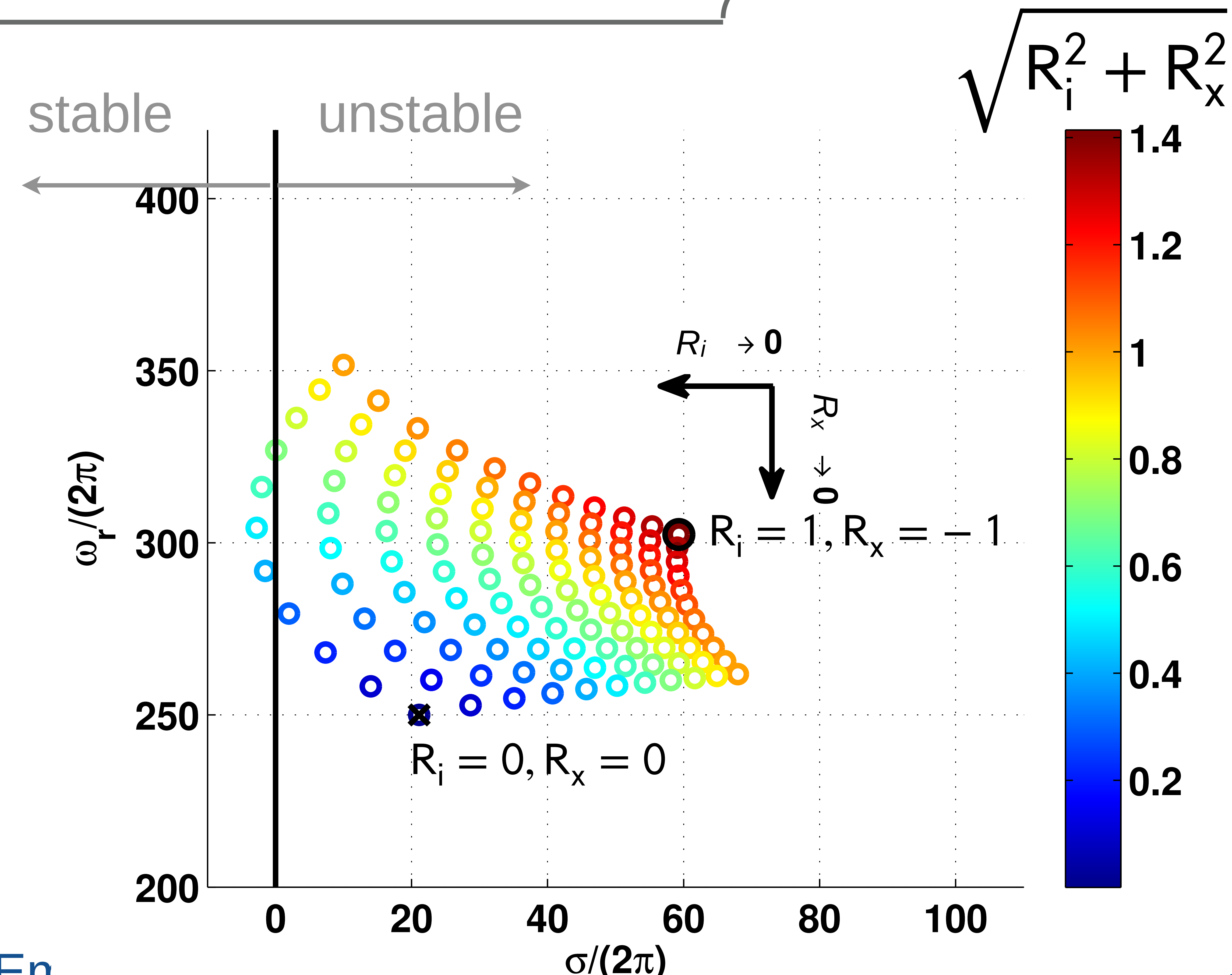


Intrinsic mode is unstable if the interaction index n is supercritical,

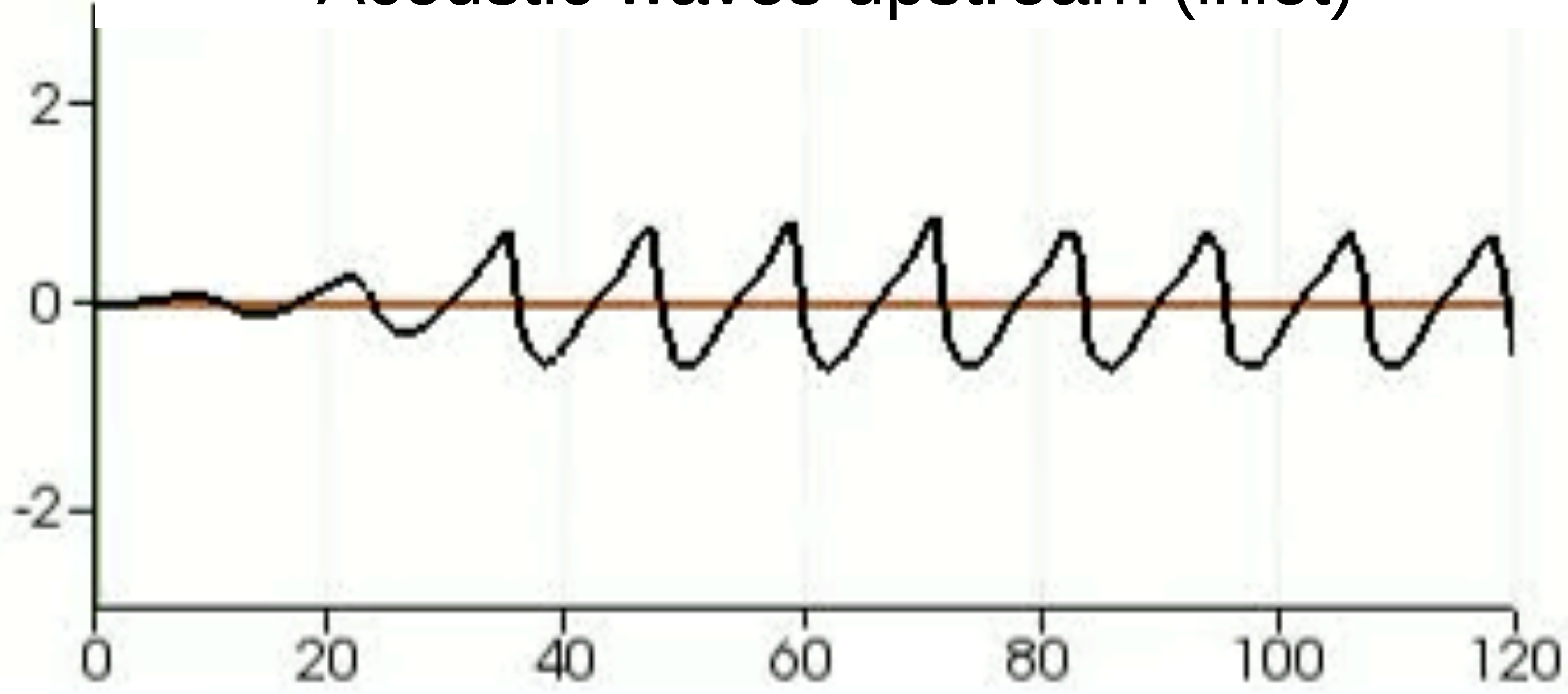
$$n > n_c = \frac{1+\xi}{\theta}$$

and the phase of the FTF = π

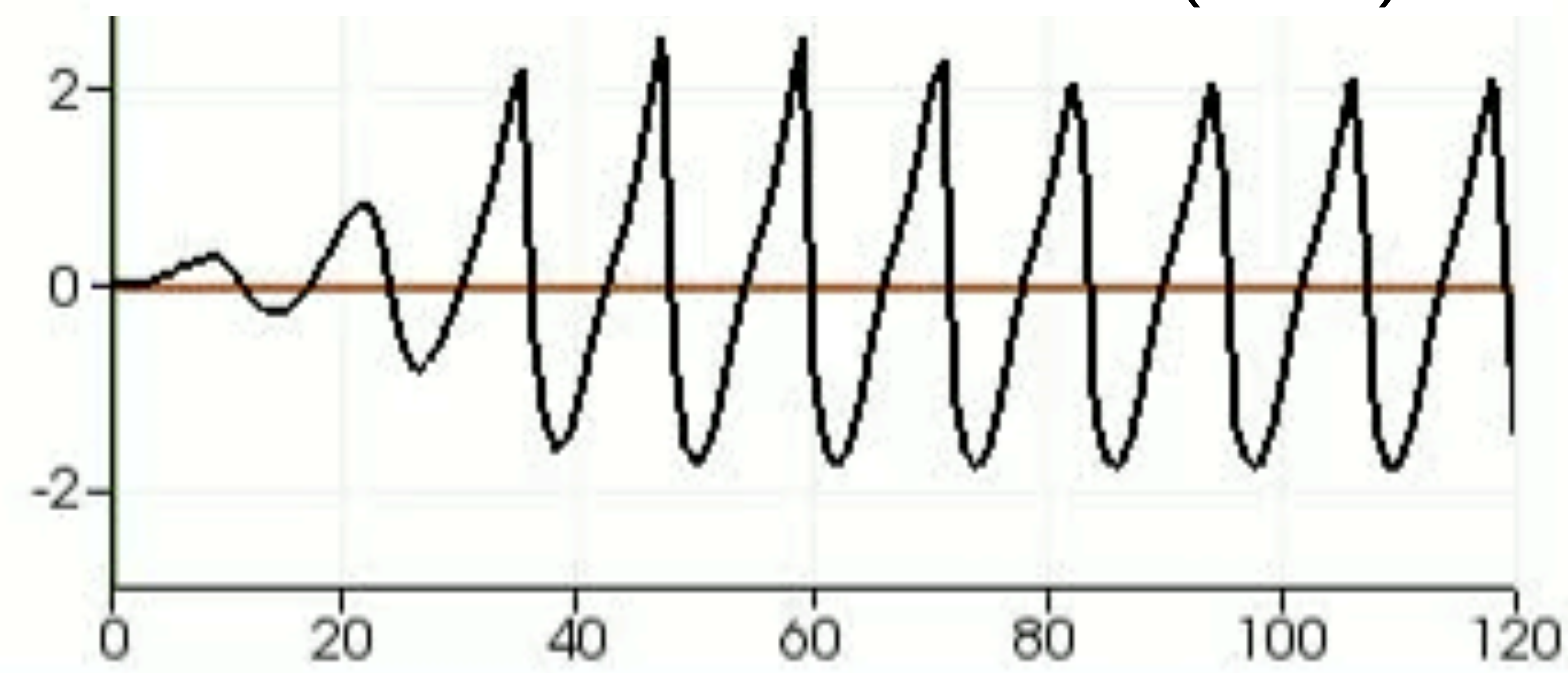
$$\omega\tau = \pi$$

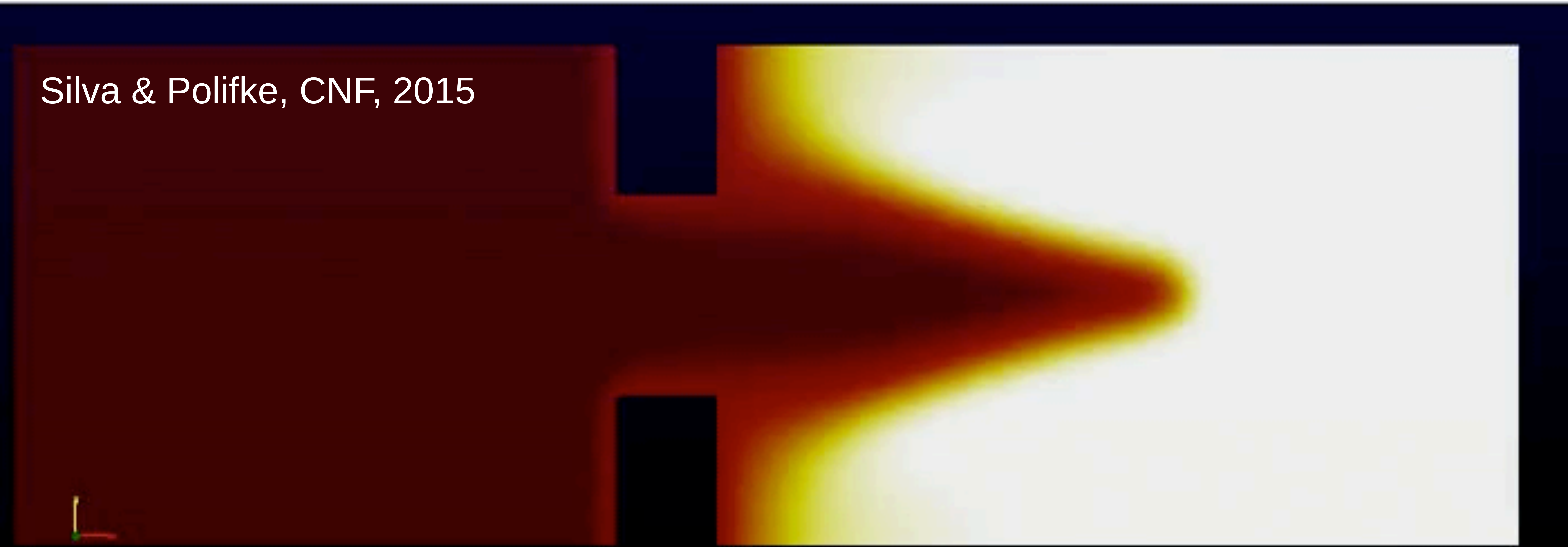


Acoustic waves upstream (inlet)



Acoustic waves downstream (outlet)





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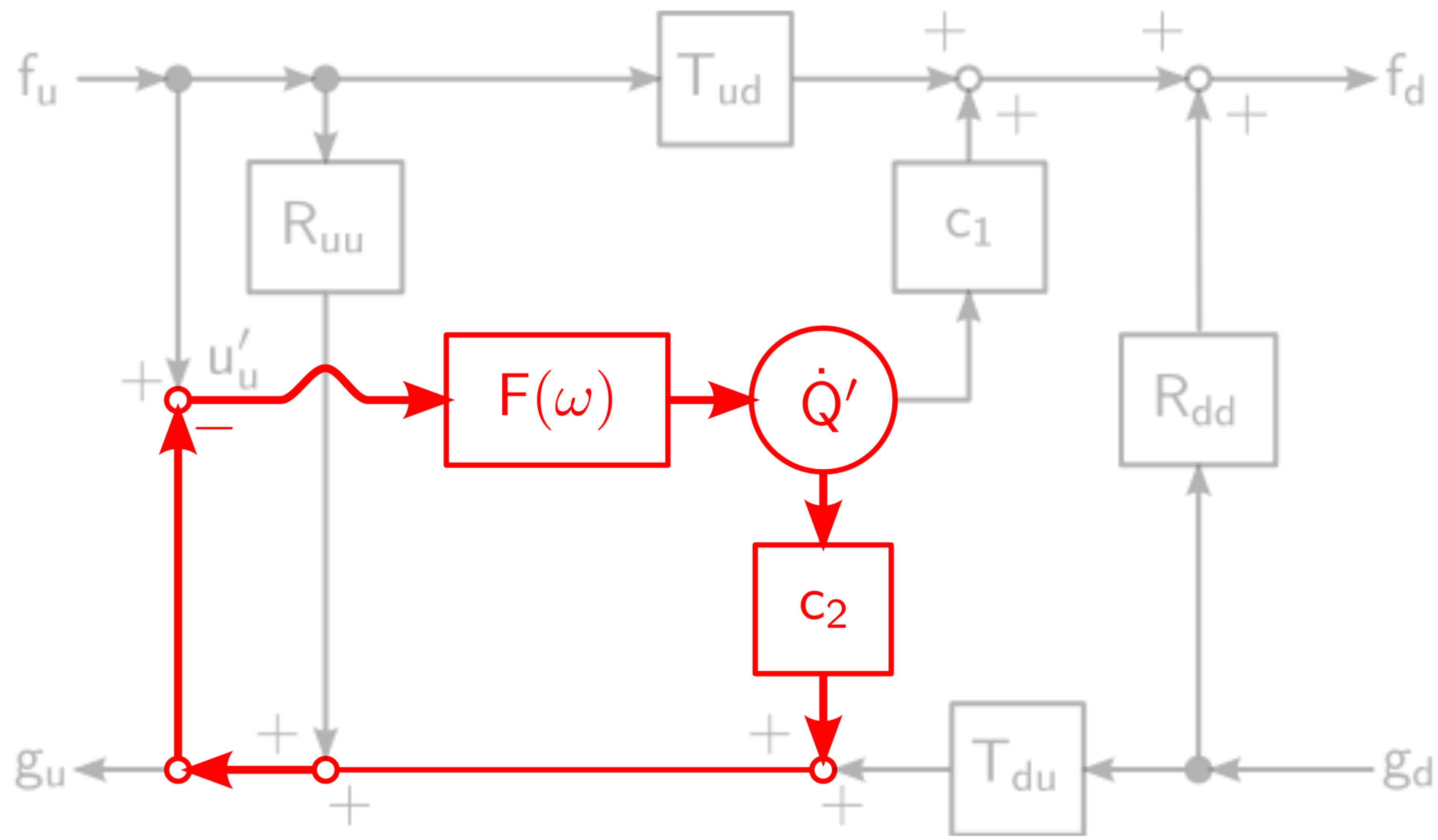
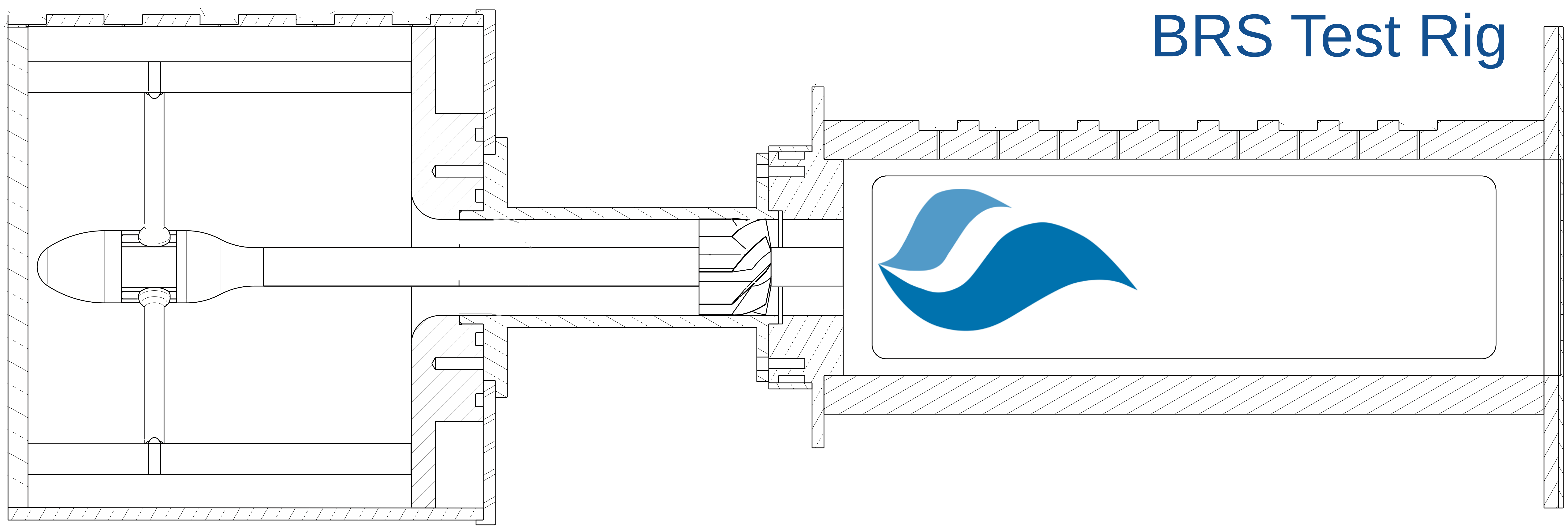
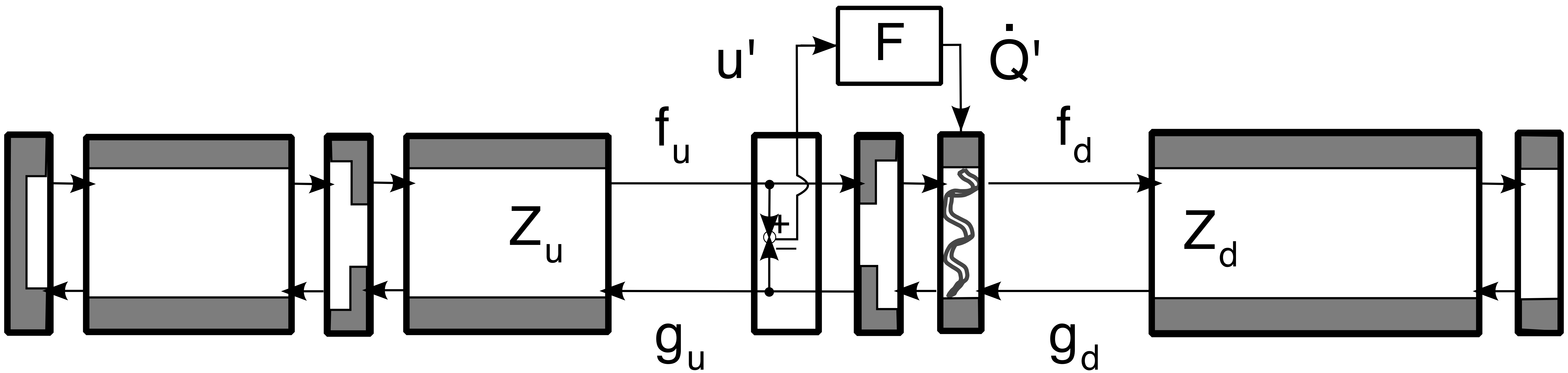


ITA feedback is important also if reflection coefficients are non-zero !





Emmert et al, PROCI 2017

Re-arrange system matrix to segregate the network model into acoustic and ITA sub-systems, which may then be de-coupled

$$0 = \underbrace{\begin{bmatrix} -1 & \frac{Z_u+1}{Z_u-1} & 0 & 0 & 0 & 0 \\ \frac{\alpha-\xi}{\alpha+\xi} & -1 & 0 & \frac{2}{\alpha+\xi} & 0 & \frac{\theta}{\alpha+\xi} \\ \frac{2\alpha\xi}{\alpha+\xi} & 0 & -1 & \frac{\xi-\alpha}{\alpha+\xi} & 0 & \frac{\xi\theta}{\alpha+\xi} \\ 0 & 0 & \frac{Z_d-1}{Z_d+1} & -1 & 0 & 0 \\ 1 & -1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & F & -1 \end{bmatrix}}_{A(s)} \begin{bmatrix} f_u \\ g_u \\ f_d \\ g_d \\ u_u \\ \dot{q}' \end{bmatrix}$$

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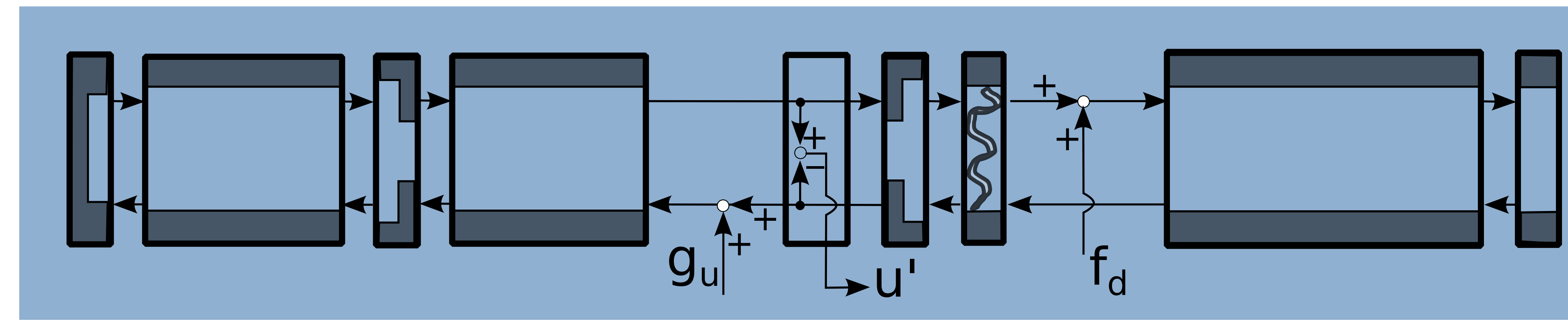
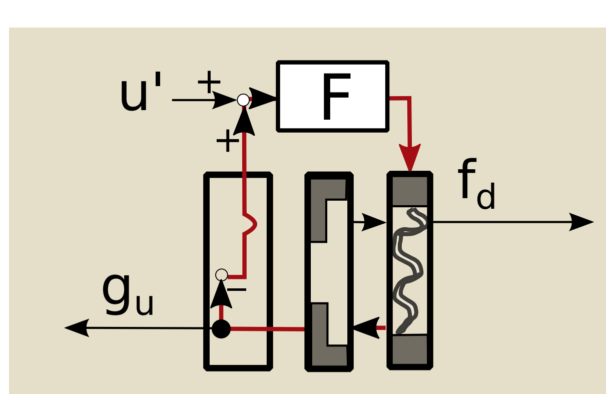


$$0 = \underbrace{\left[\begin{array}{cccc|cc} -1 & \frac{Z_u+1}{Z_u-1} & 0 & 0 & 0 & \mu\frac{Z_u+1}{Z_u-1}\frac{\theta}{\alpha+\xi} \\ \frac{\alpha-\xi}{\alpha+\xi} & -1 & 0 & \frac{2}{\alpha+\xi} & 0 & 0 \\ \frac{2\alpha\xi}{\alpha+\xi} & 0 & -1 & \frac{\xi-\alpha}{\alpha+\xi} & 0 & \mu\frac{\xi\theta}{\alpha+\xi} \\ 0 & 0 & \frac{Z_d-1}{1+Z_d} & -1 & 0 & 0 \\ \hline \mu & -\mu & 0 & 0 & -1 & -\frac{\theta}{\alpha+\xi} \\ 0 & 0 & 0 & 0 & F & -1 \end{array}\right]}_{\tilde{A}(s)} \begin{bmatrix} f_u \\ g_u \\ f_d \\ g_d \\ u_u \\ \dot{q}' \end{bmatrix}$$

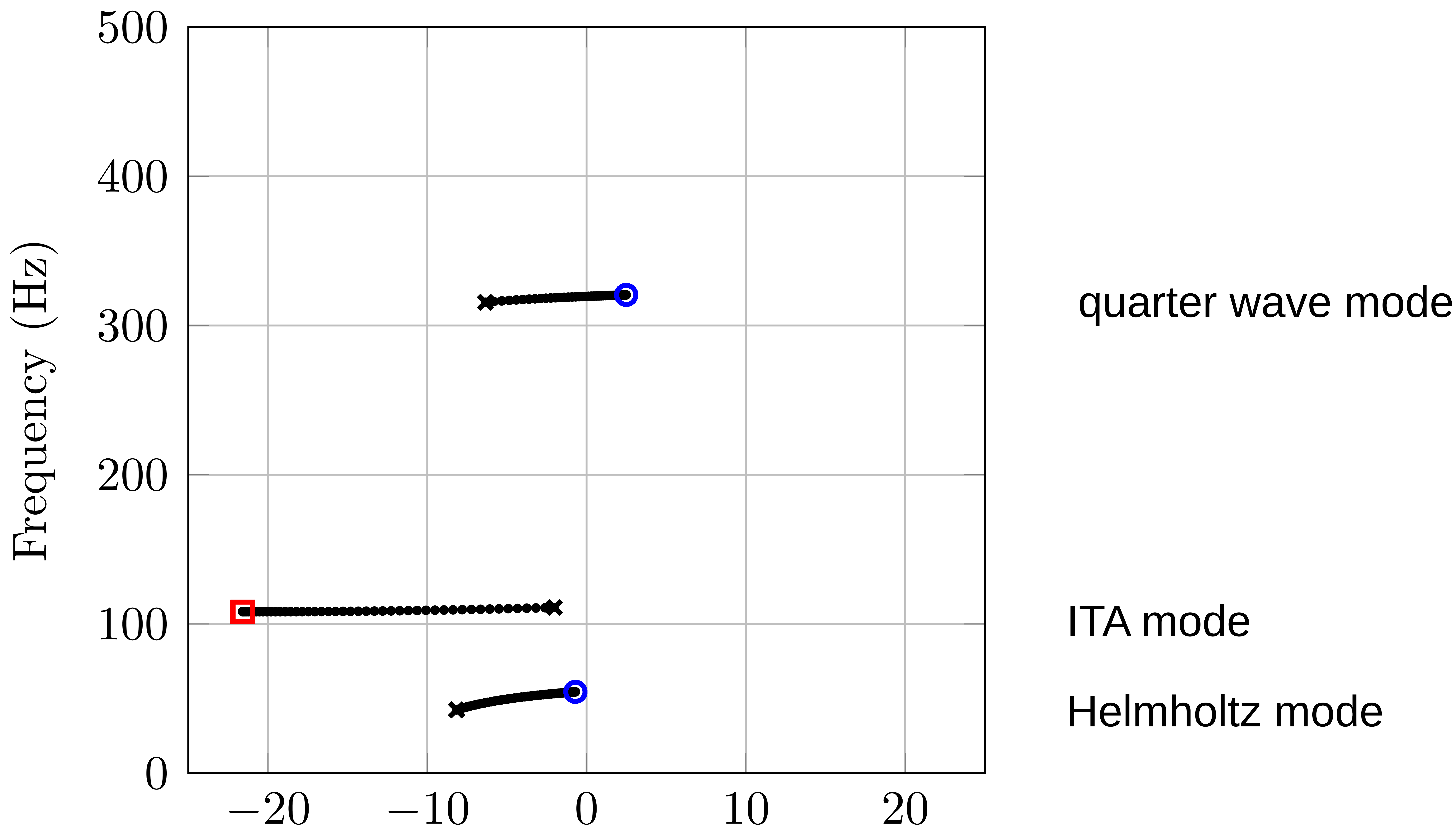


Emmert et al, PROCI 2017

Variation of the coupling coefficient $\mu : 1 \rightarrow 0$ associates a thermoacoustic mode with cavity *acoustics* or the *ITA* feedback loop

$R_i = +1$

$R_x = -1$



Sub-systems:

- ○ acoustic
- □ ITA
- ✖ full system

Emmert et al, PROCI 2017

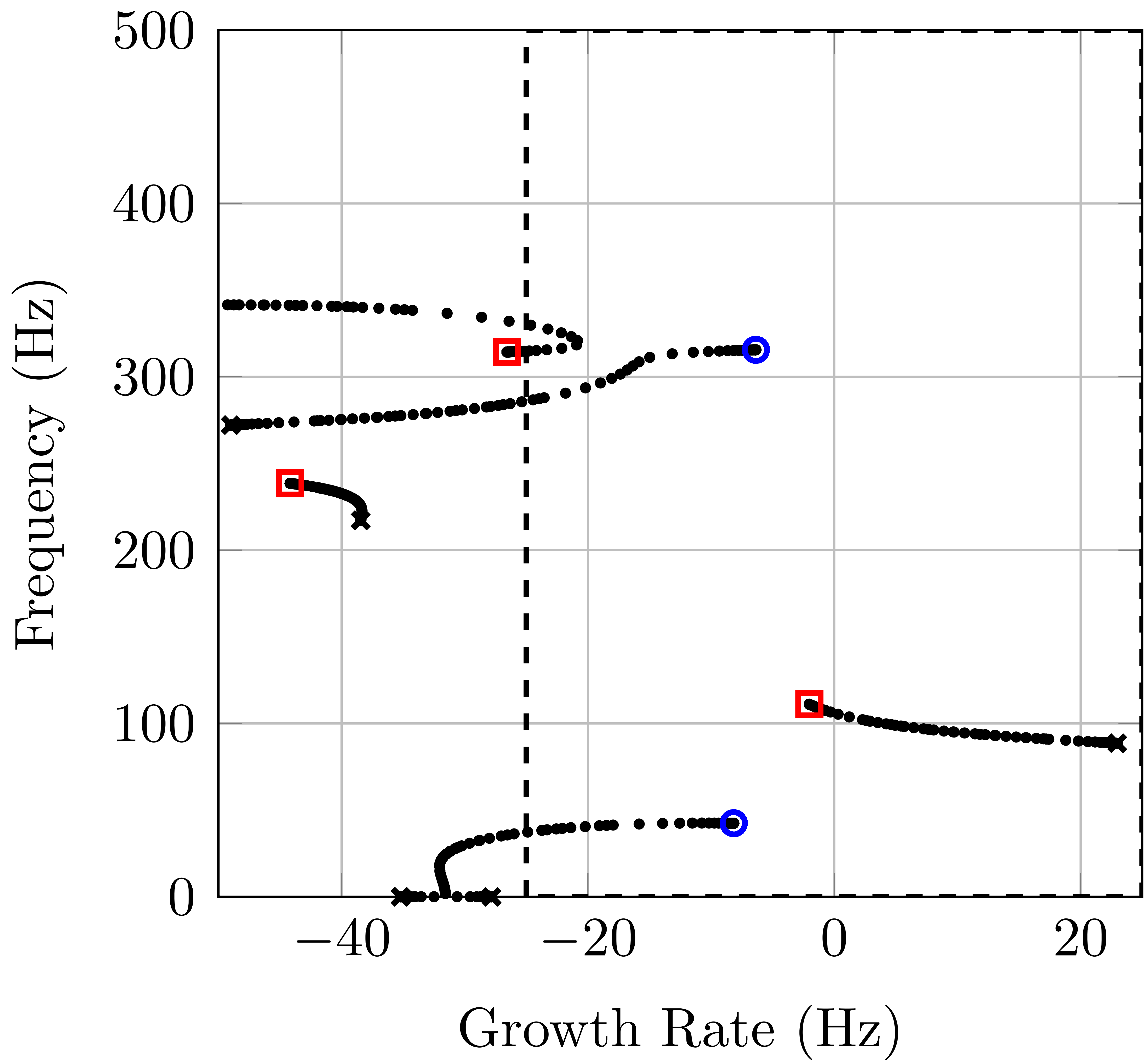
Anomalous behaviour of the dominant ITA mode: with *decreasing* reflection at the exit, R_x = -1 → 0 its growth rate *increases*

$R_i = +1$

$R_x = -1 \rightarrow 0$

○ → ×

□ → ×



□ ITA mode

○ 1/4 wave mode

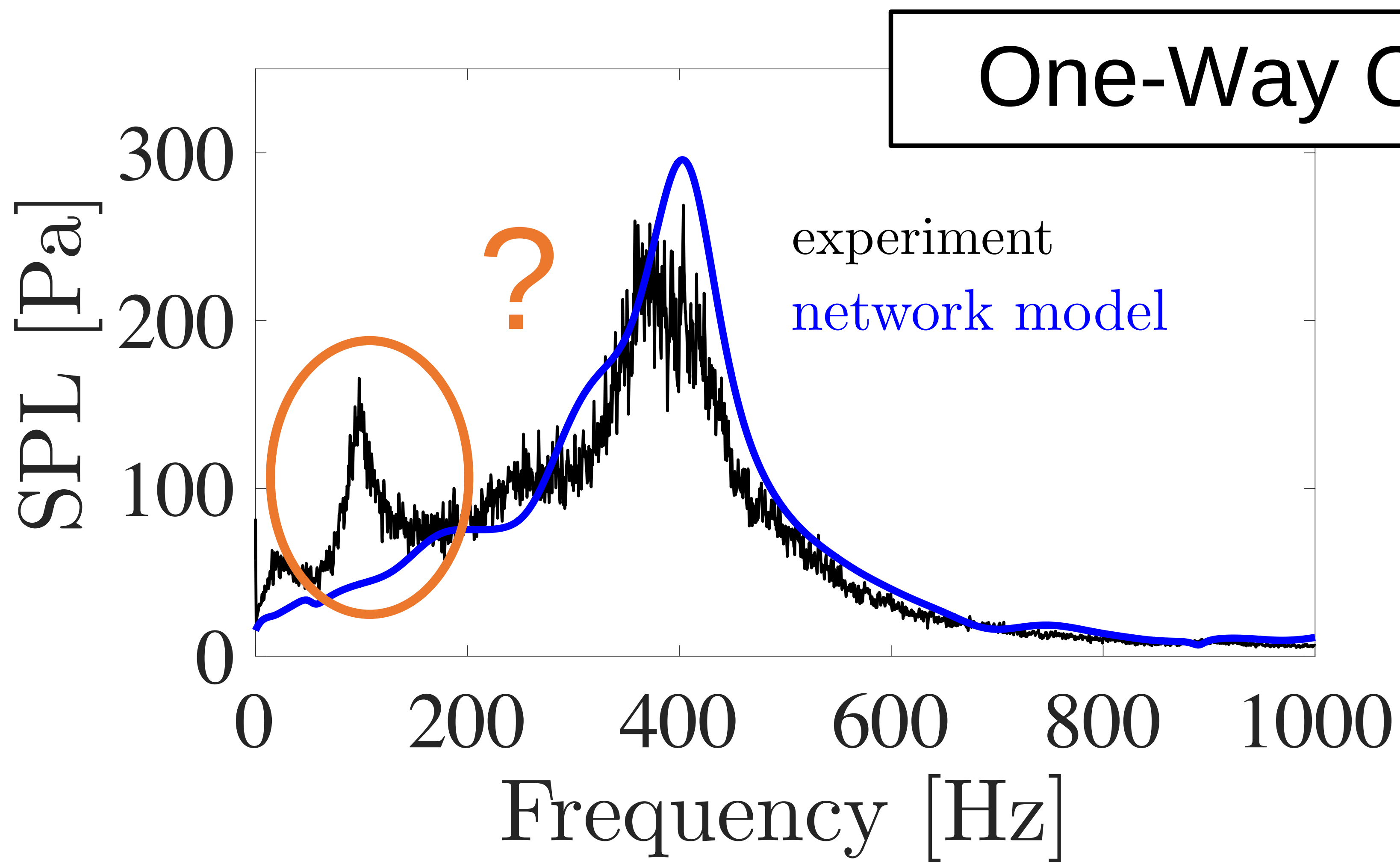
□ ITA mode

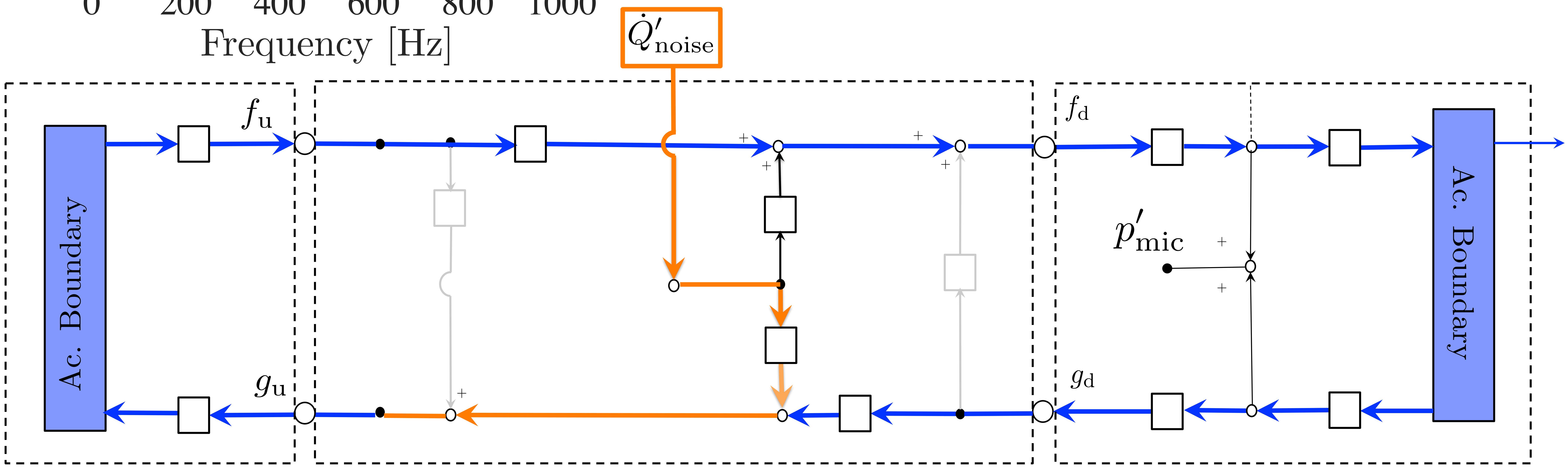
□ ITA mode

○ Helmholtz mode

Emmert et al, PROCI 2017

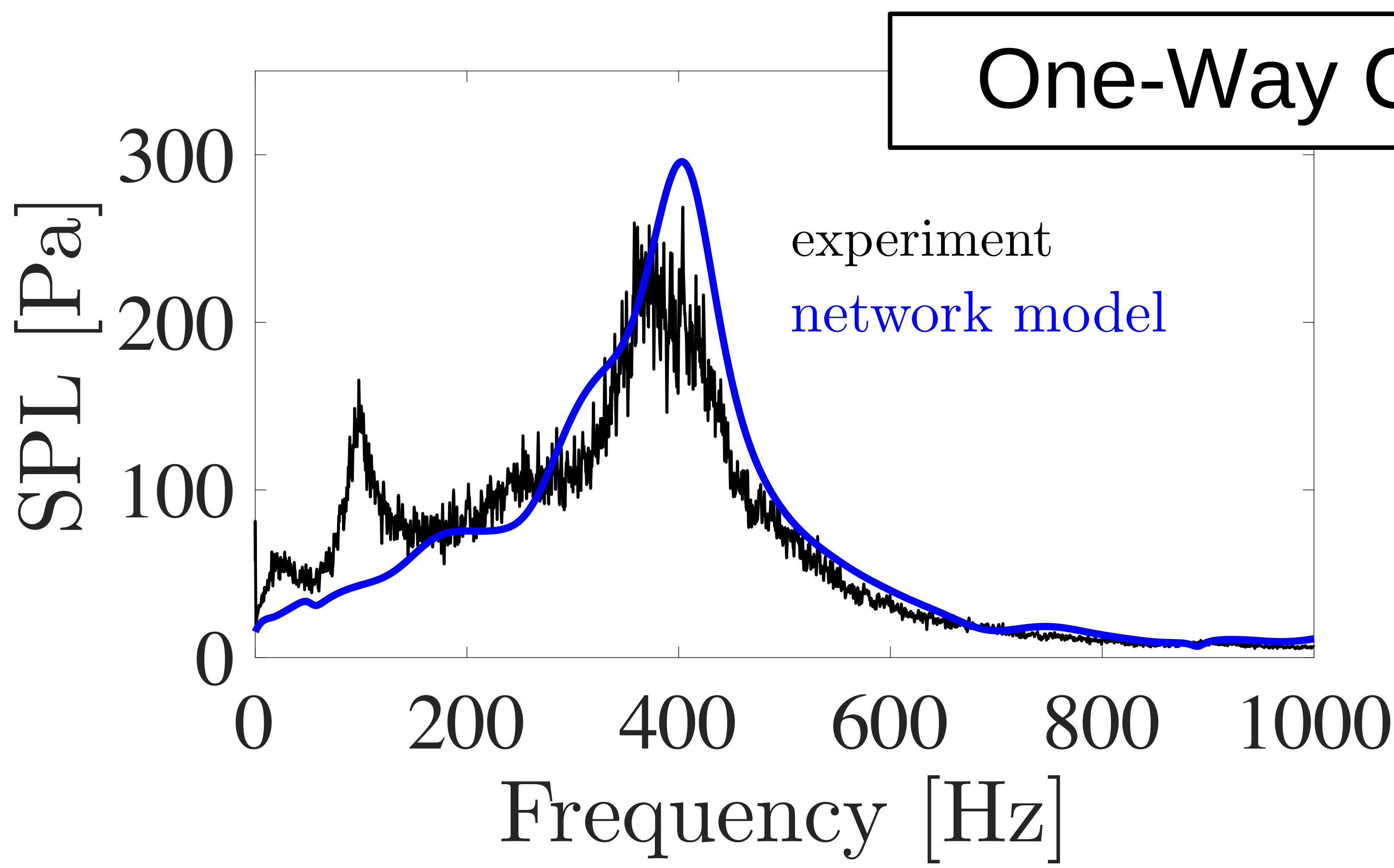
One-way coupling between combustion noise source and combustor acoustics yields a resonance peak at 400 Hz - the quarter wave mode of the combustor

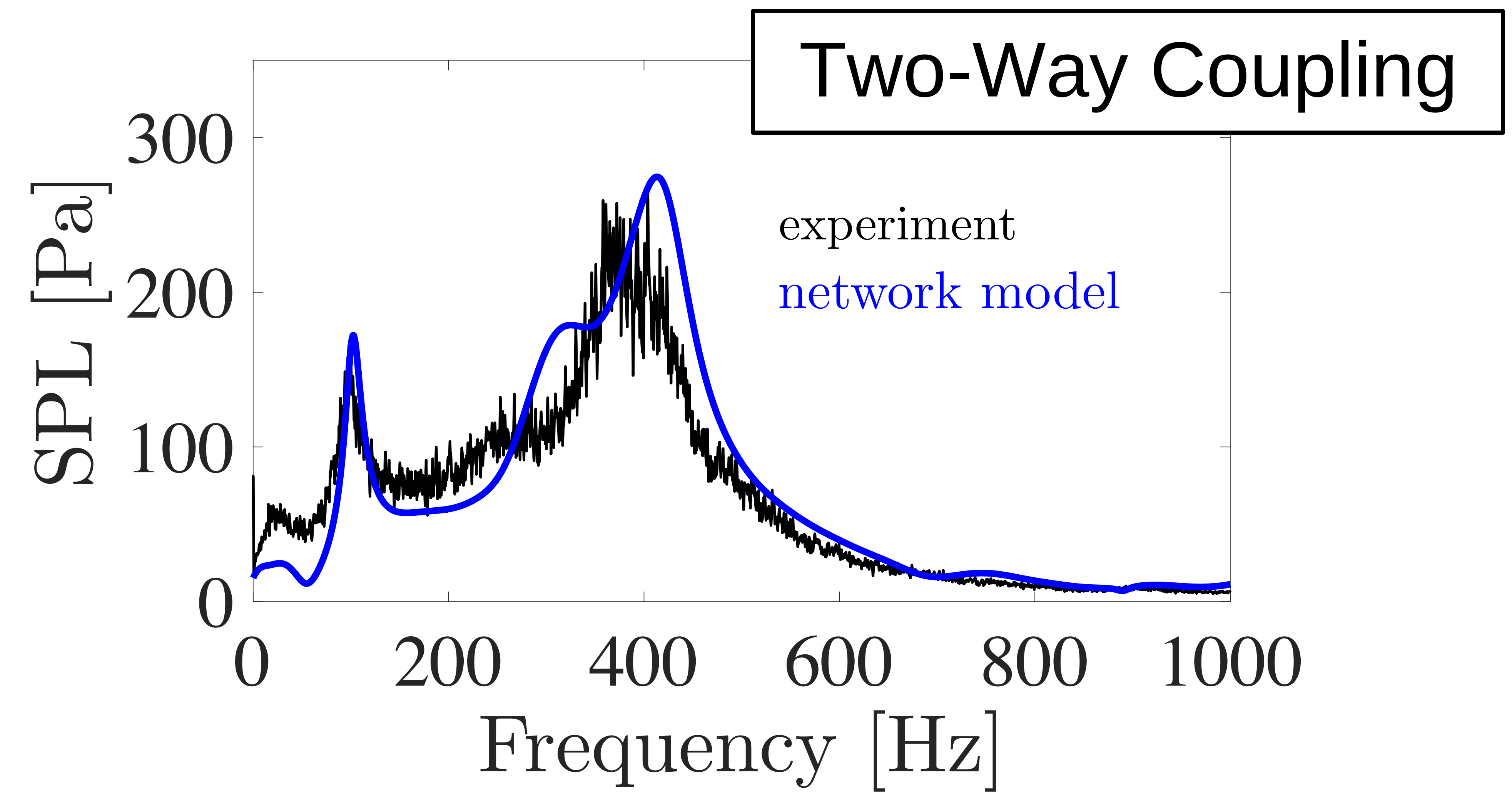


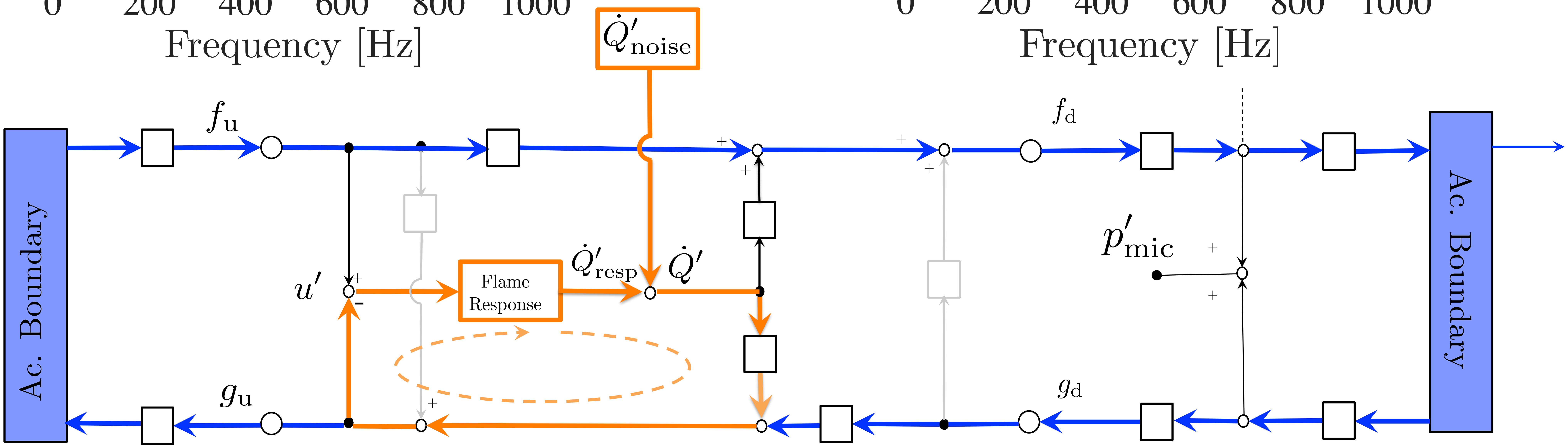


Silva et al, TIGRE, 2016, CNF 2017

With two-way coupling, we recover also the low-frequency peak, and identify it as resonance of the noise source term with the ITA feedback loop







Silva et al, TIGRE, 2016, CNF 2017

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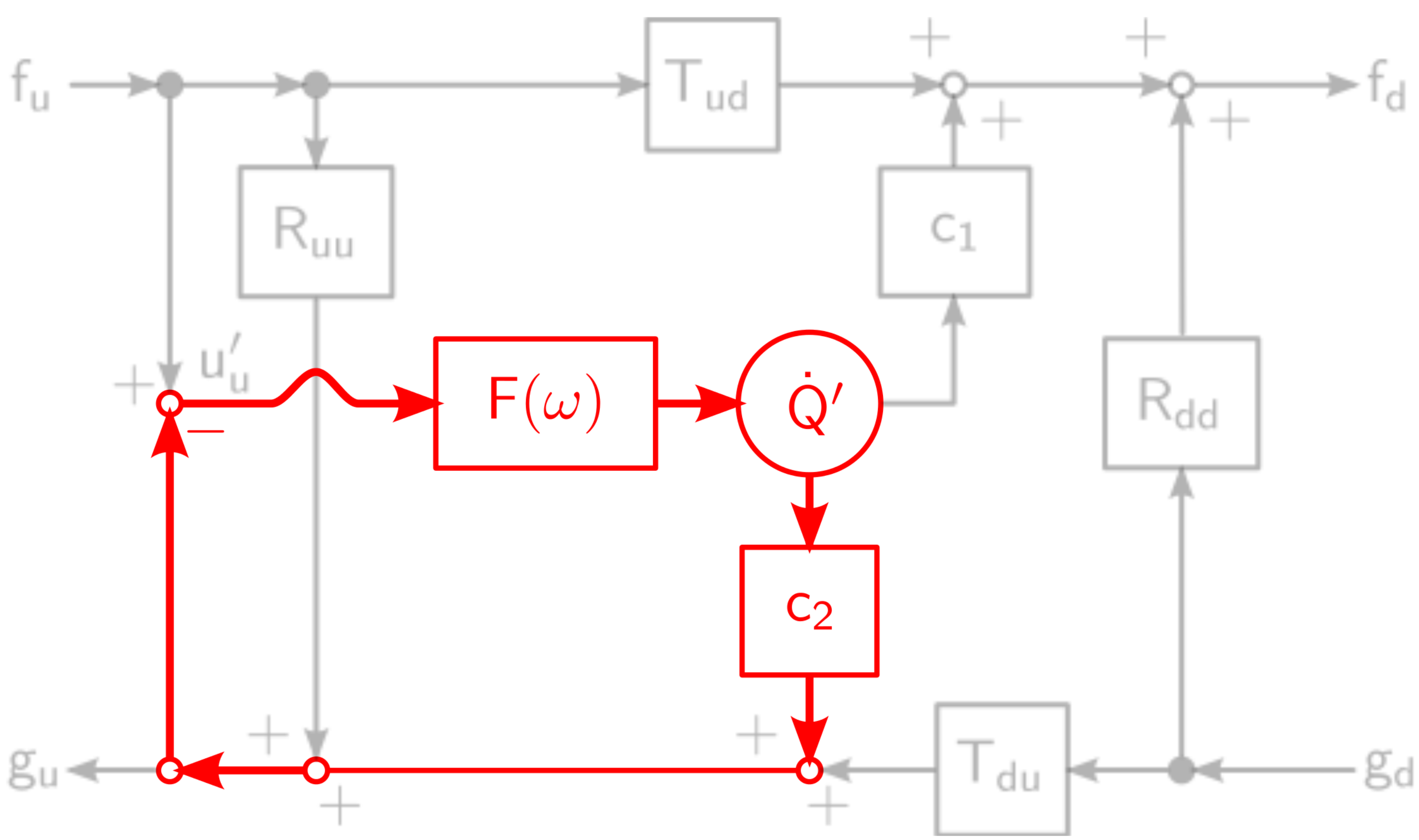
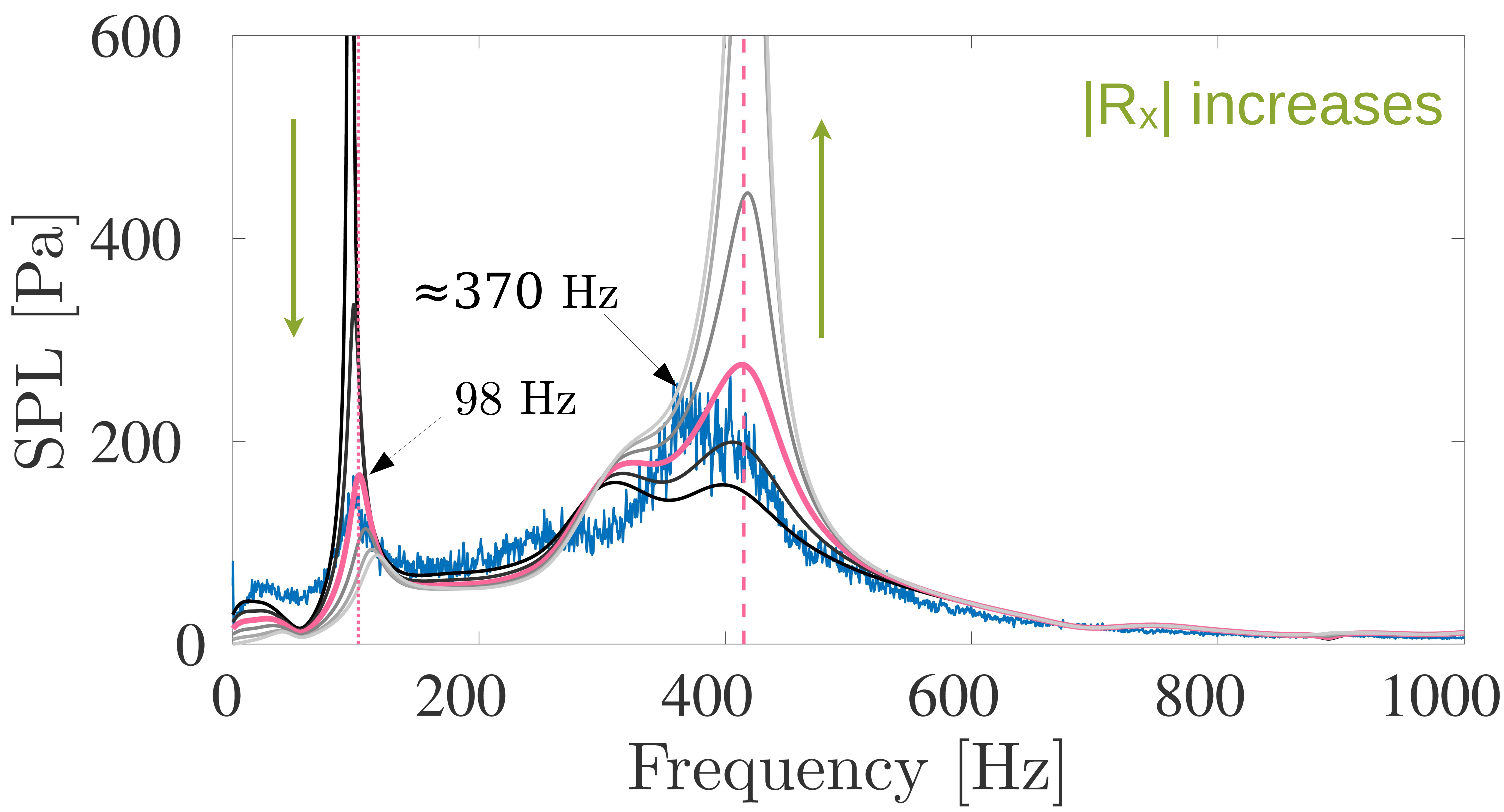
Exceptional points and clusters

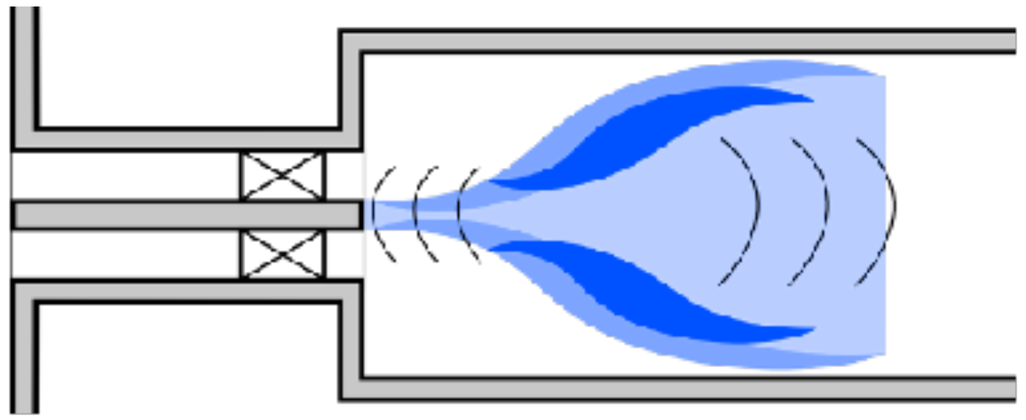


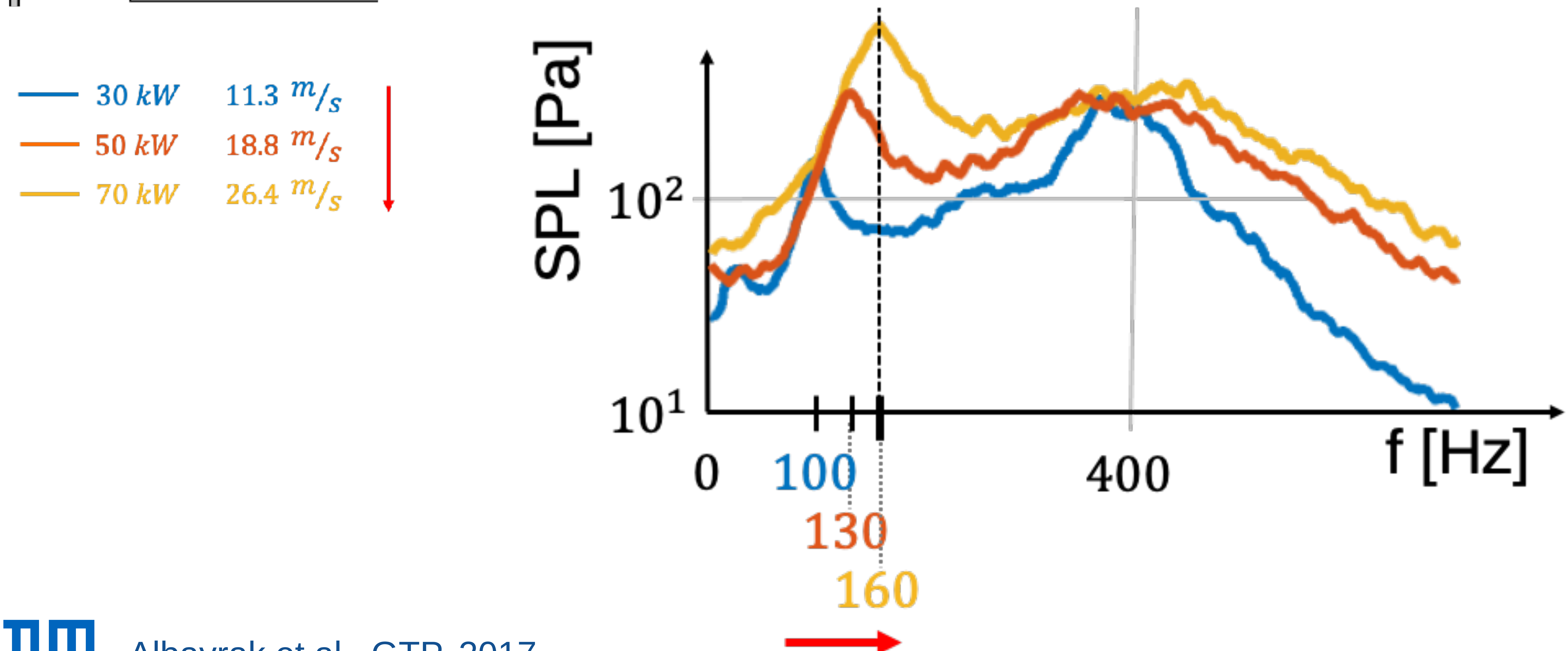
Again, the ITA resonance peak shows non-intuitive response to variation in the exit reflection coefficient



Silva et al, TIGRE, 2016, CNF 2017

For constant equivalence ratio, temperature, speed of sound the ITA peak frequency increases with flow speed – *convective scaling*

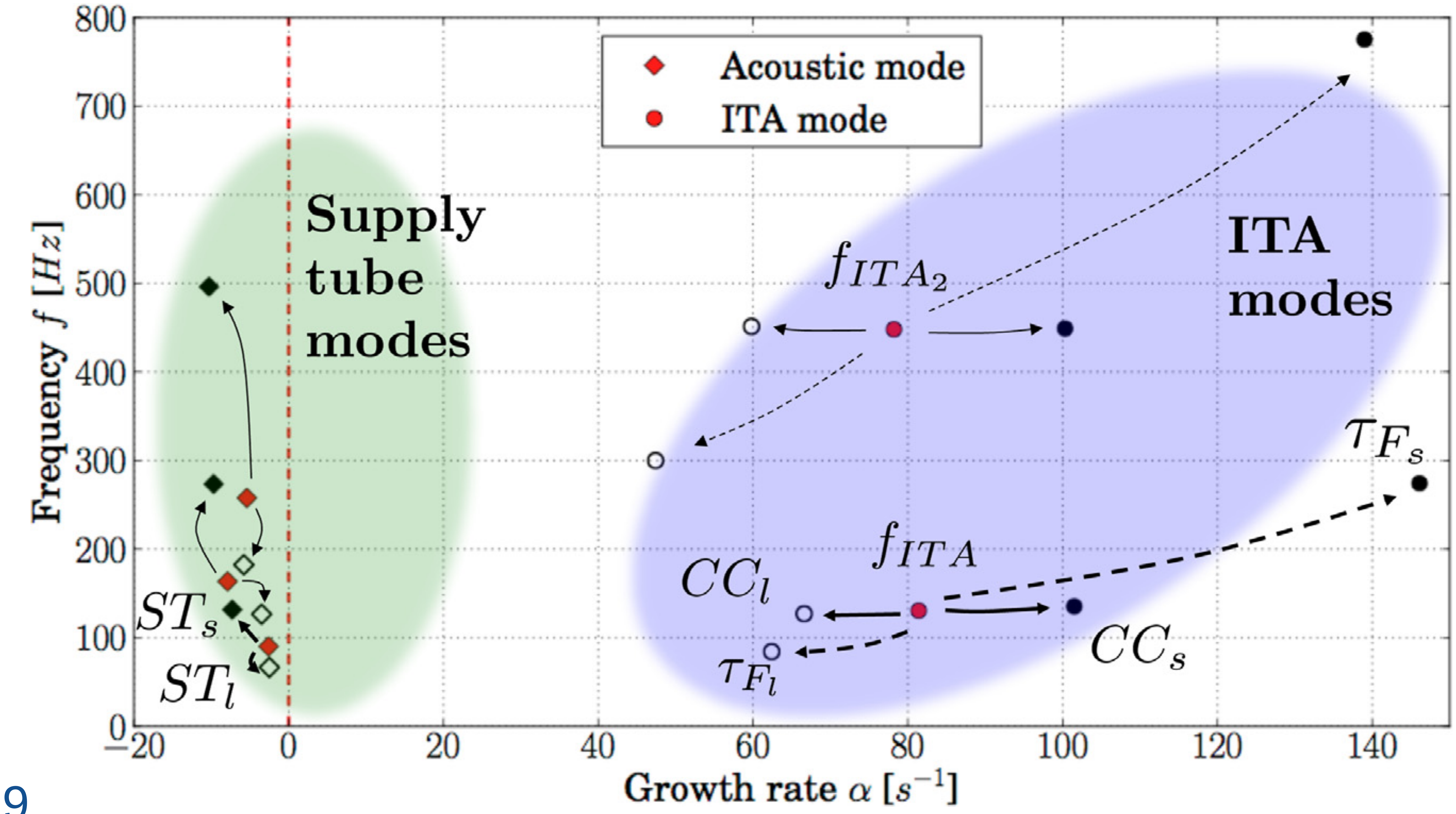




Albayrak et al., GTP, 2017

Convective scaling helped to identify a low frequency „bulk mode” in a spray flame combustor as an ITA mode

Eckstein et al., JPP, GTP, 2006



Ghani et al., CNF, 2019

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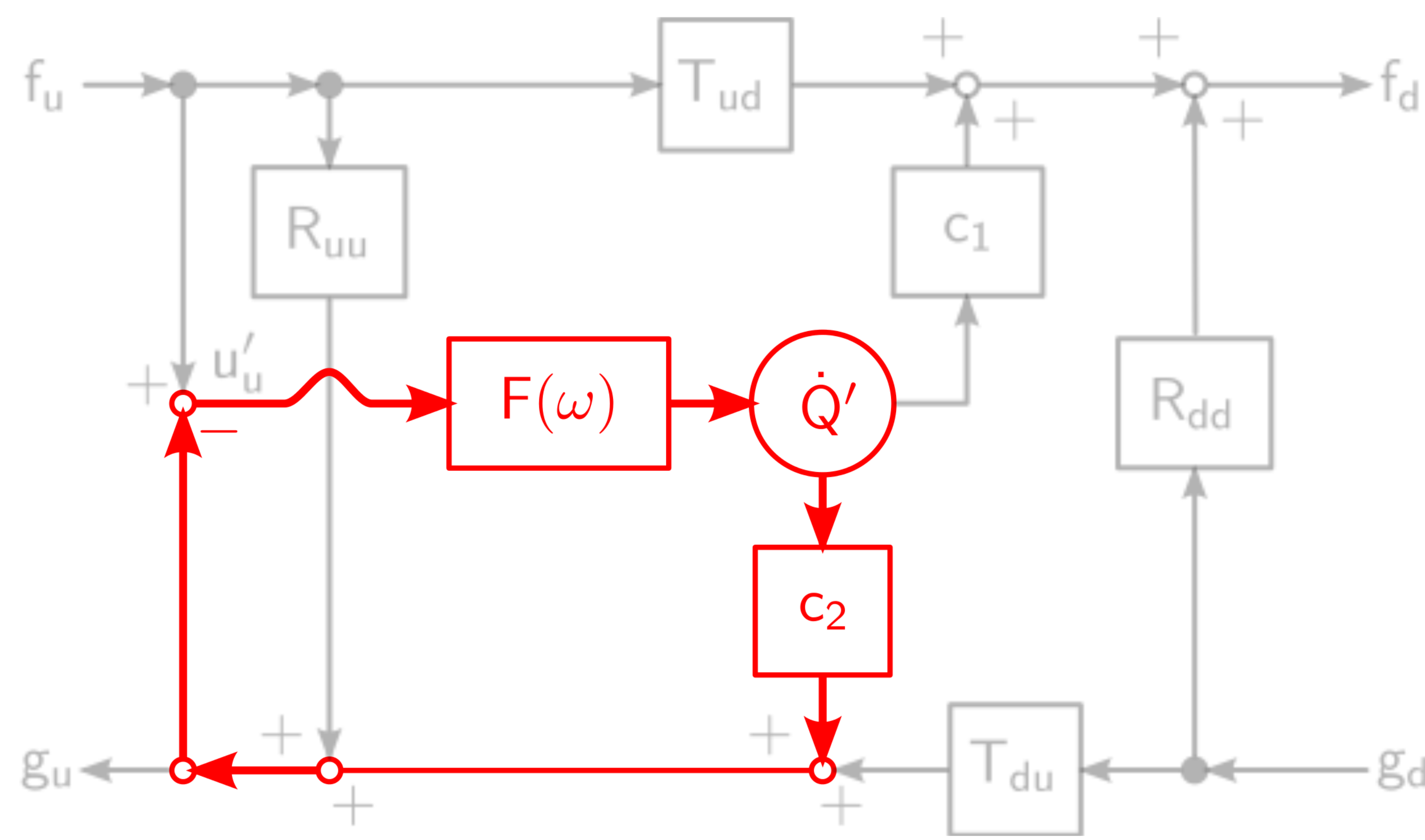
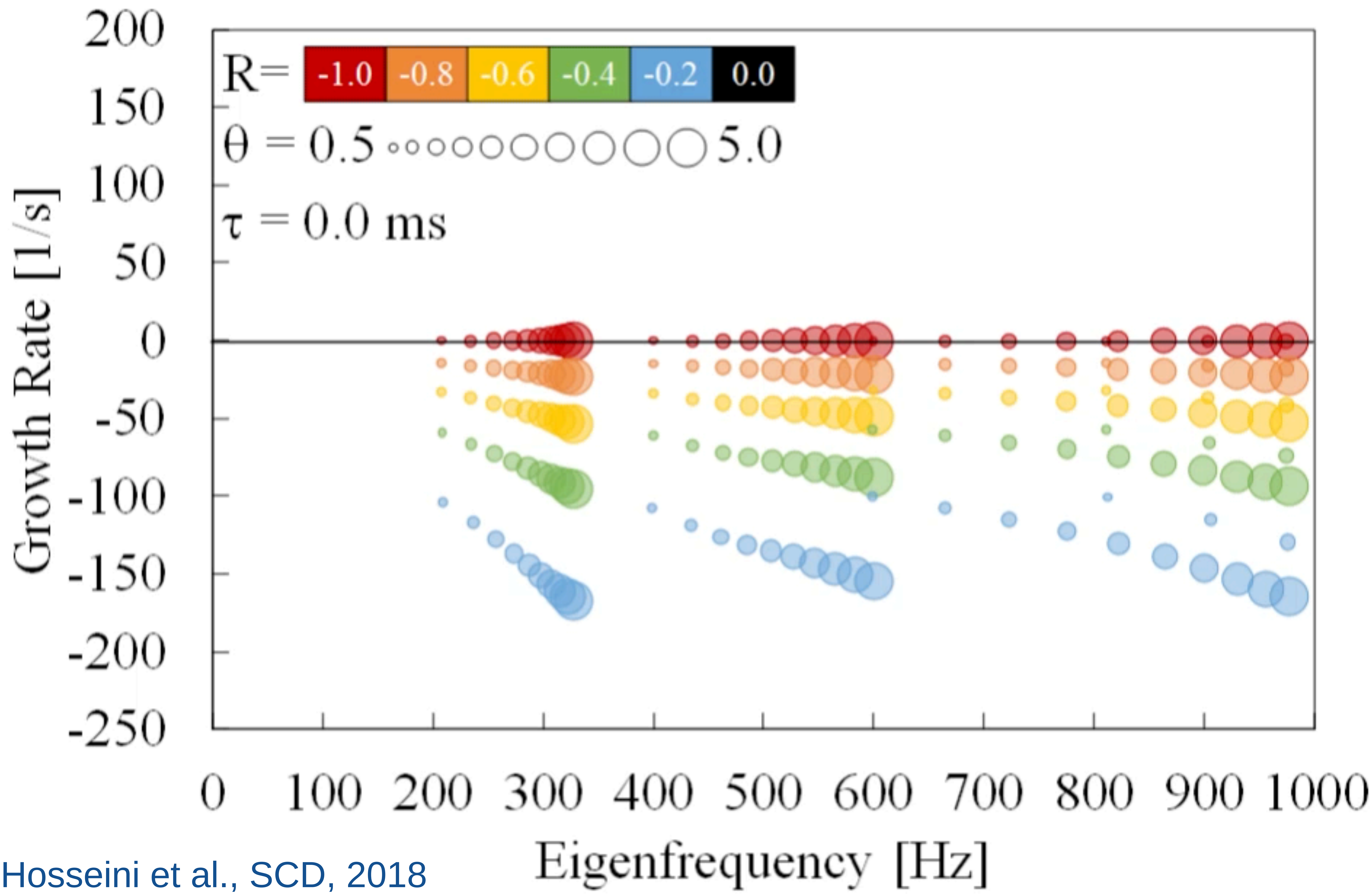
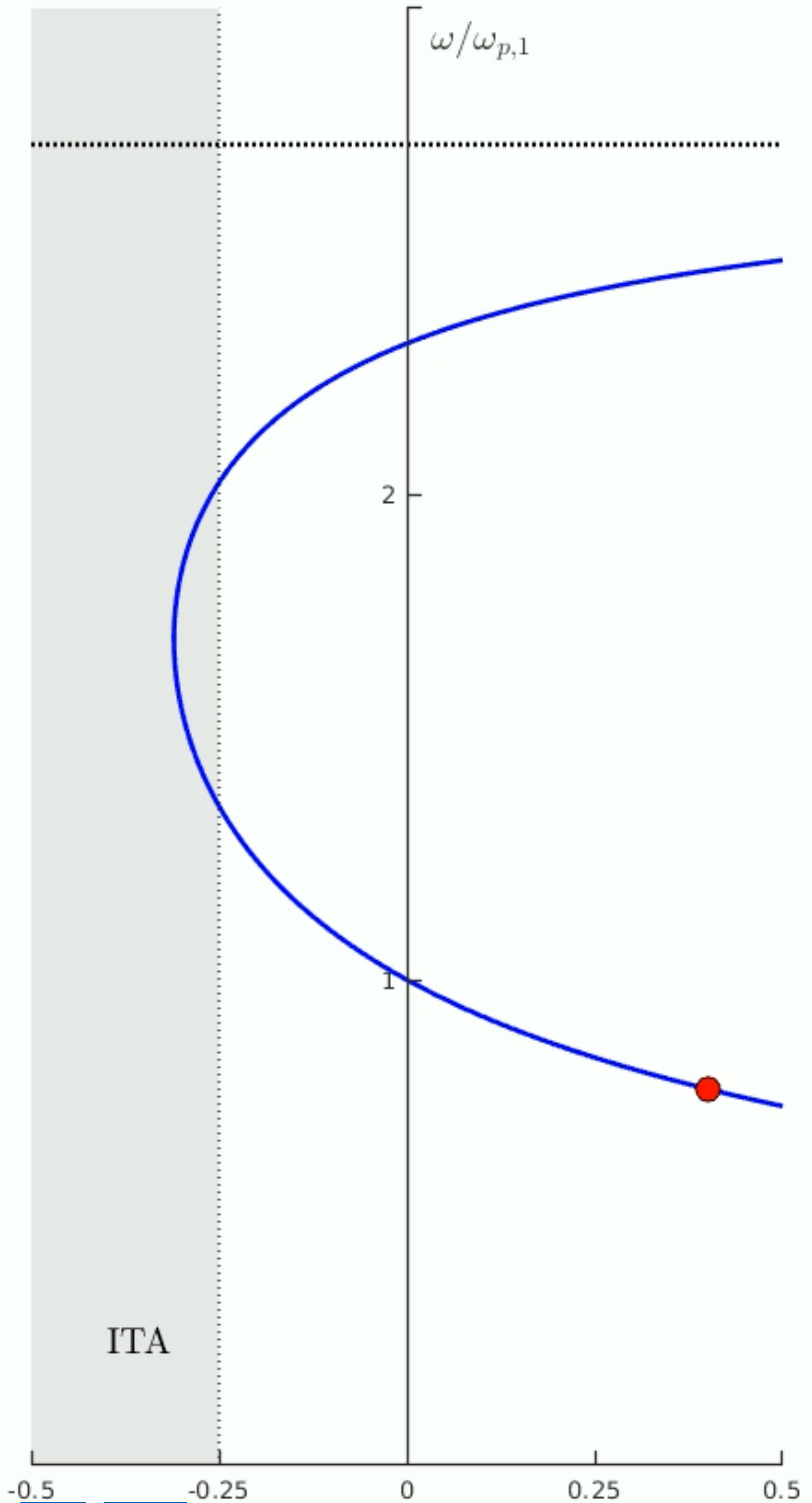


ITA modes seem to „interplay” with acoustic modes and change identity

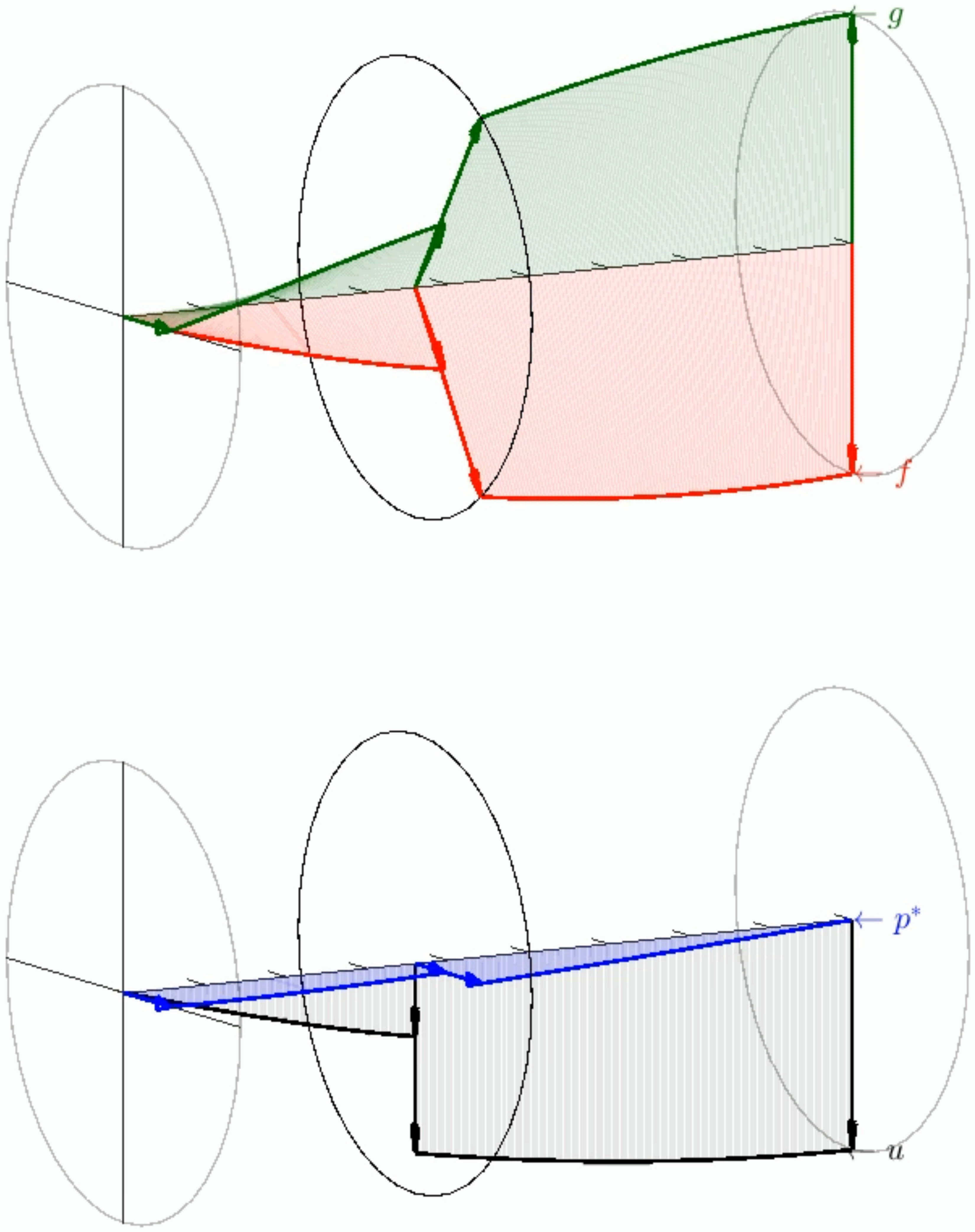


Hosseini et al., SCD, 2018

Phasor analysis reveals the nature (ITA/acoustic) of marginally stable modes in an ideal resonator



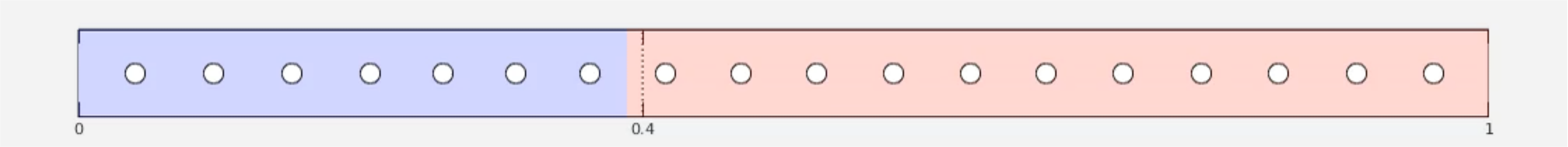
Acoustic mode



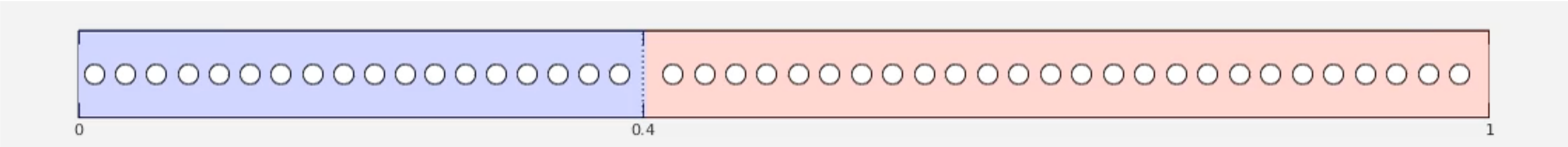
Yong et al., CNF, 2021

Animations help to interpret phasor diagrams of cavity and ITA modes

Cavity modes *sloshes back and forth* across the heat source



ITA modes are 1D *push-pull* modes



Yong et al., CNF, 2022 (?)

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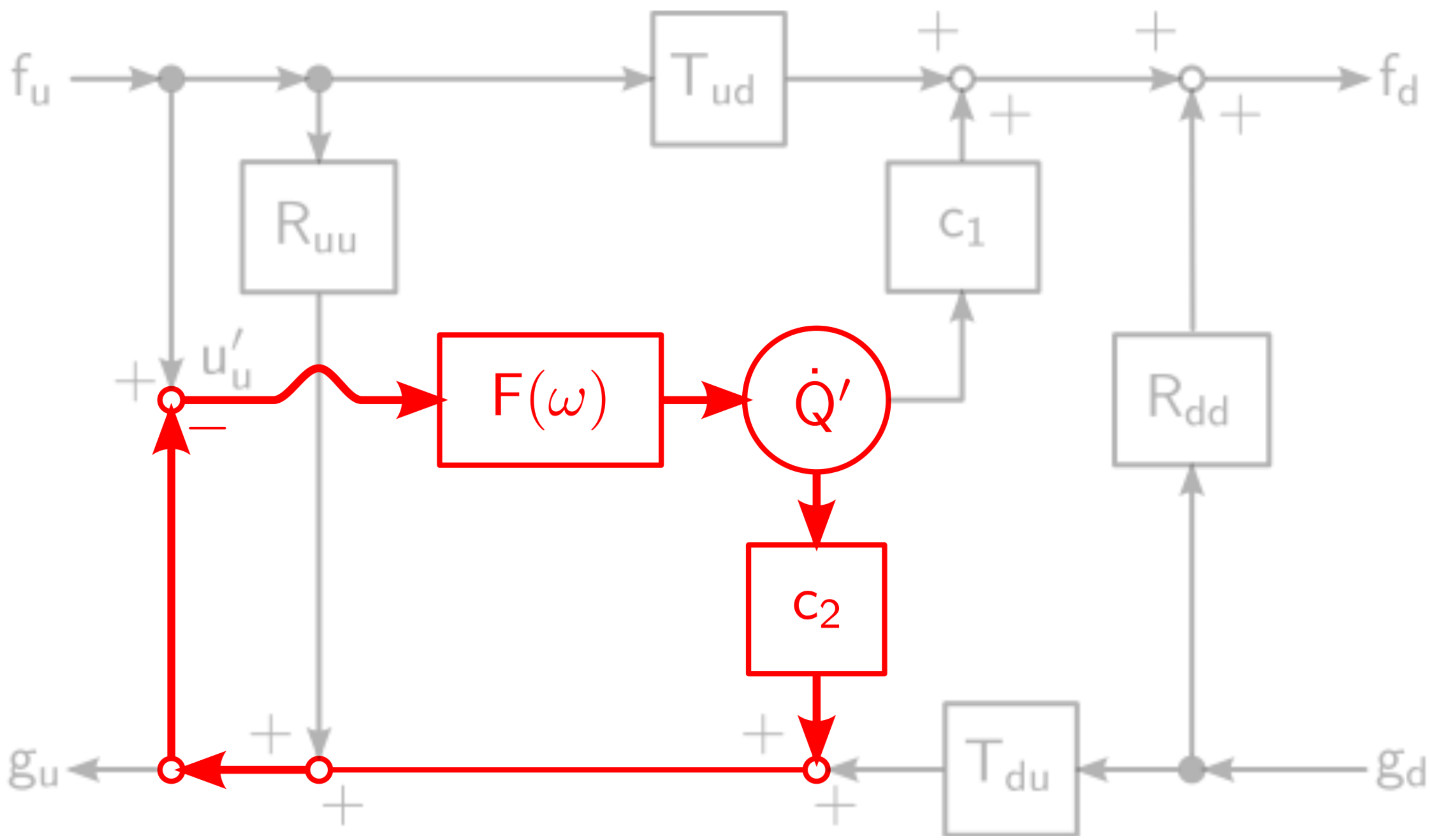
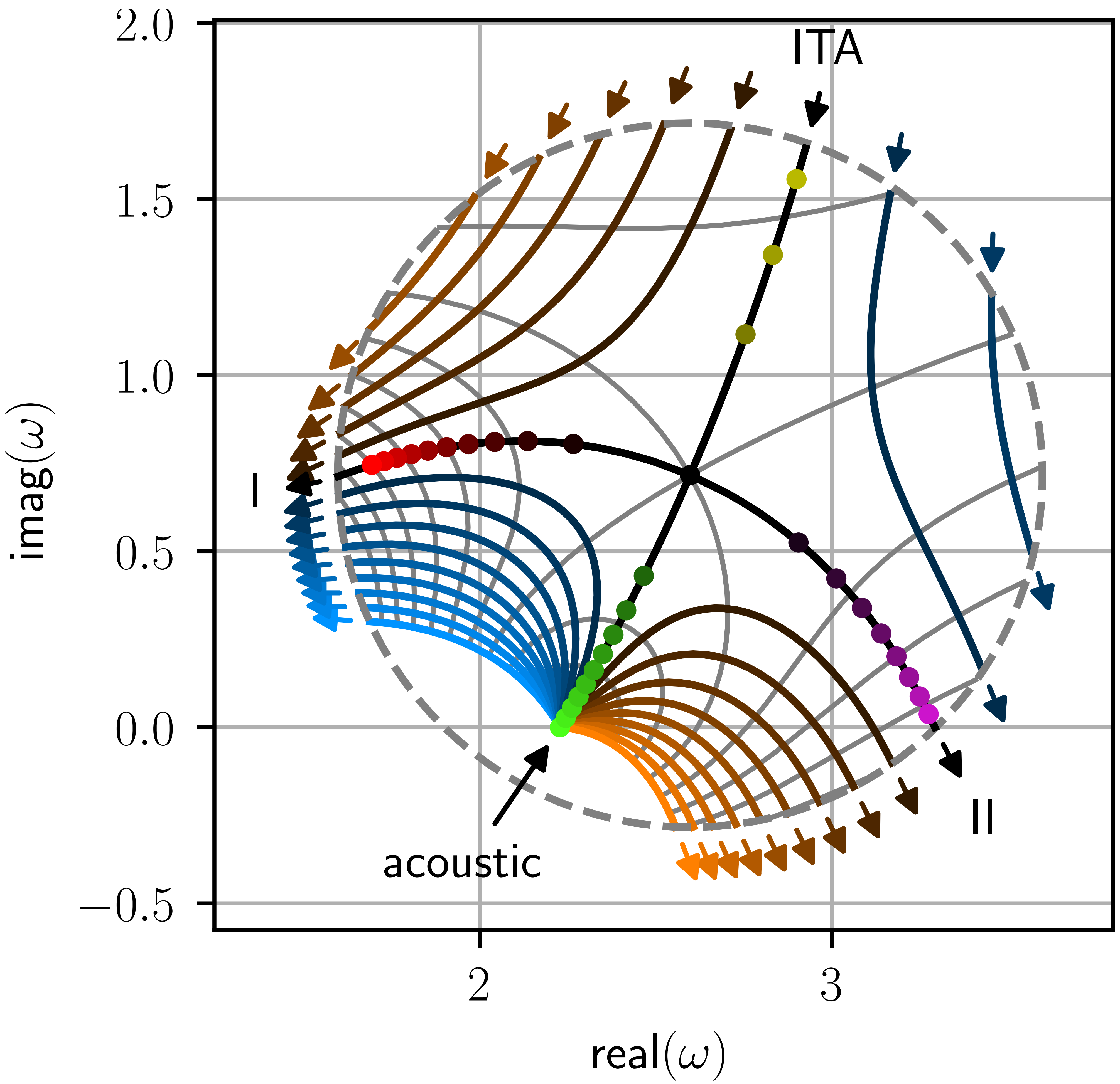
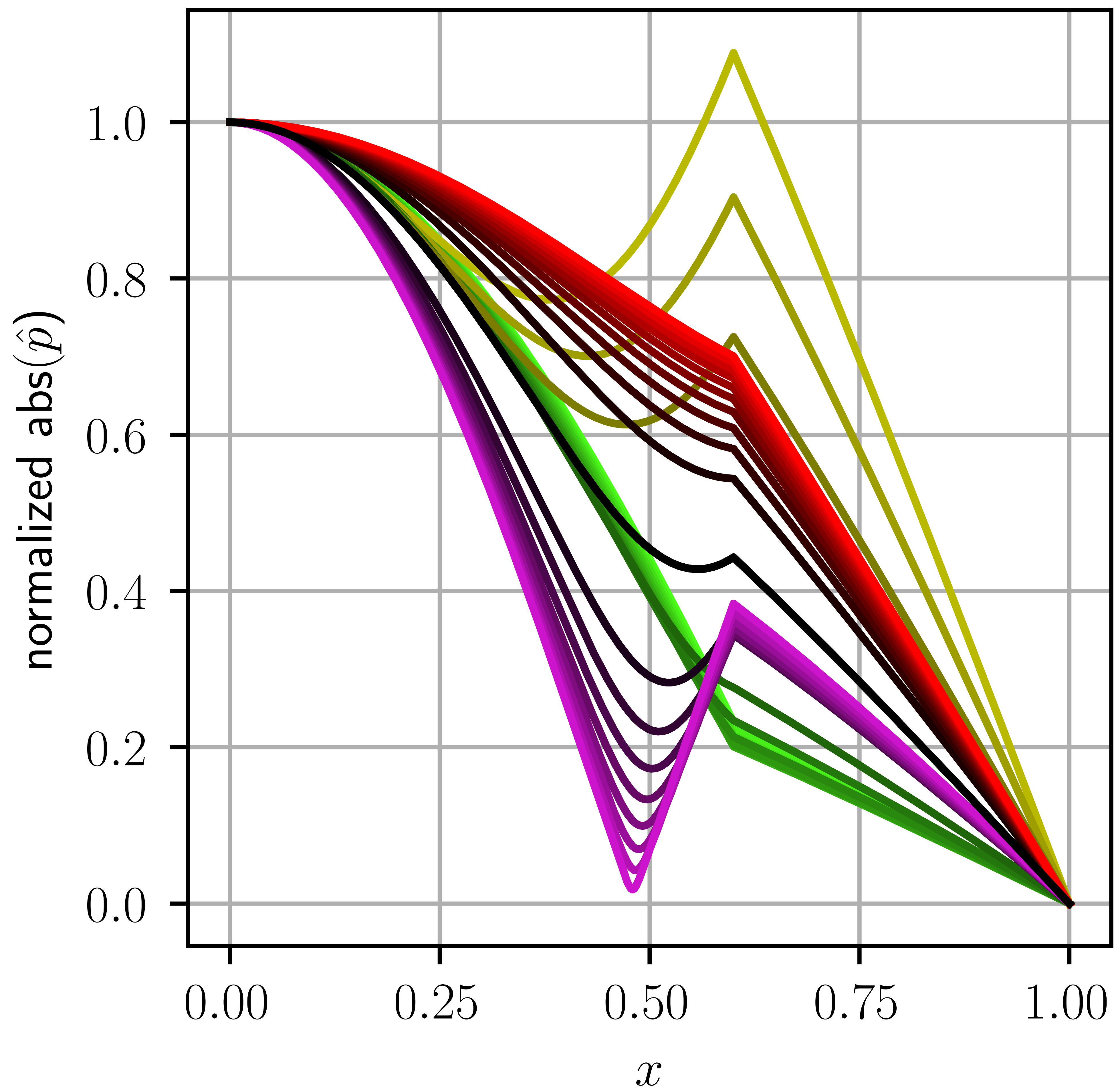


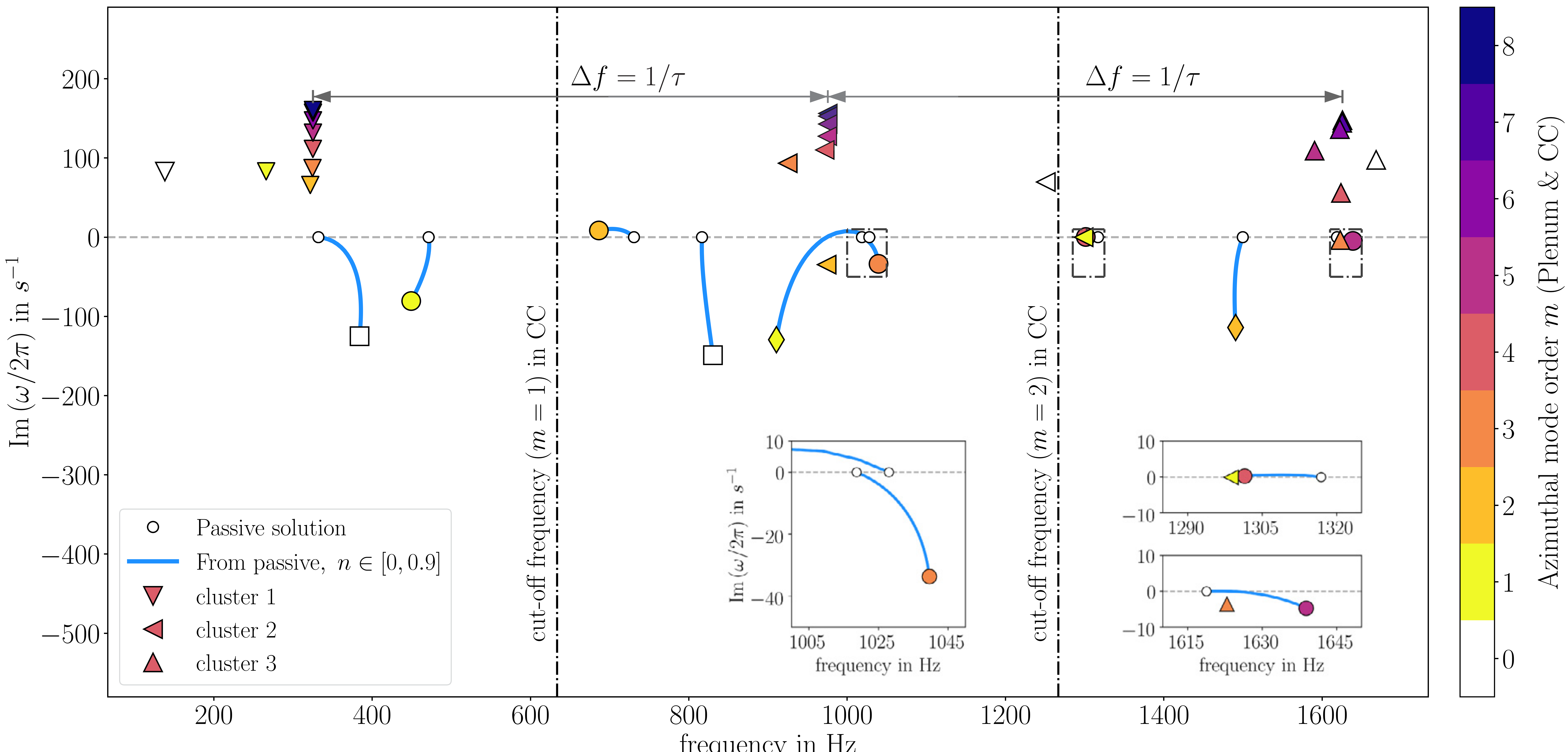
With variation of flame parameters n, τ
ITA modes and cavity modes interact at exceptional points





Mensah et al., CNF, 2018 (see also Orchini et al., CNF, 2020)

The annular MICCA combustor exhibits acustic and clusters of ITA modes



Buschmann et al., CNF, 2020

Publications

Bomberg, S., Emmert, T., and Polifke, W., "Thermal Versus Acoustic Response of Velocity Sensitive Premixed Flames," *Proceedings of the Combustion Institute*, vol. 35 (3), 2015, pp. 3185–3192.

Courtine, E., Selle, L., and Poinsot, T., "DNS of Intrinsic Thermoacoustic Modes in Laminar Premixed Flames," *Combustion and Flame*, vol. 162, 2015, pp. 4331–4341.

Courtine, E., Selle, L., Nicoud, F., Polifke, W., Silva, C., Bauerheim, M., and Poinsot, T., "Causality and intrinsic thermoacoustic instability modes," *Proceedings of the 2014 Summer Program*, Stanford, USA: Center for Turbulence Research, Stanford University, 2014, pp. 169–178.

Gentemann, A., and Polifke, W., "Scattering and generation of acoustic energy by a premix swirl burner," *Int'l Gas Turbine and Aeroengine Congress & Exposition*, Montreal, Quebec, Canada: 2007.

Hoeijmakers, M., Kornilov, V., Lopez Arteaga, I., de Goey, P., and Nijmeijer, H., "Intrinsic Instability of Flame-Acoustic Coupling," *Combustion and Flame*, vol. 161, Nov 2014, pp. 2860–2867.

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Noiray, N., "Analyse linéaire et non-linéaire des instabilités de combustion, application aux systèmes à injection multipoints et stratégies de contr^ole," PhD Thesis, ´Ecole Centrale Paris, 2007.

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Intrinsic thermoacoustic instability: a first review
Camilo F. Silva
PECS (forthcoming)

Summary & Conclusions

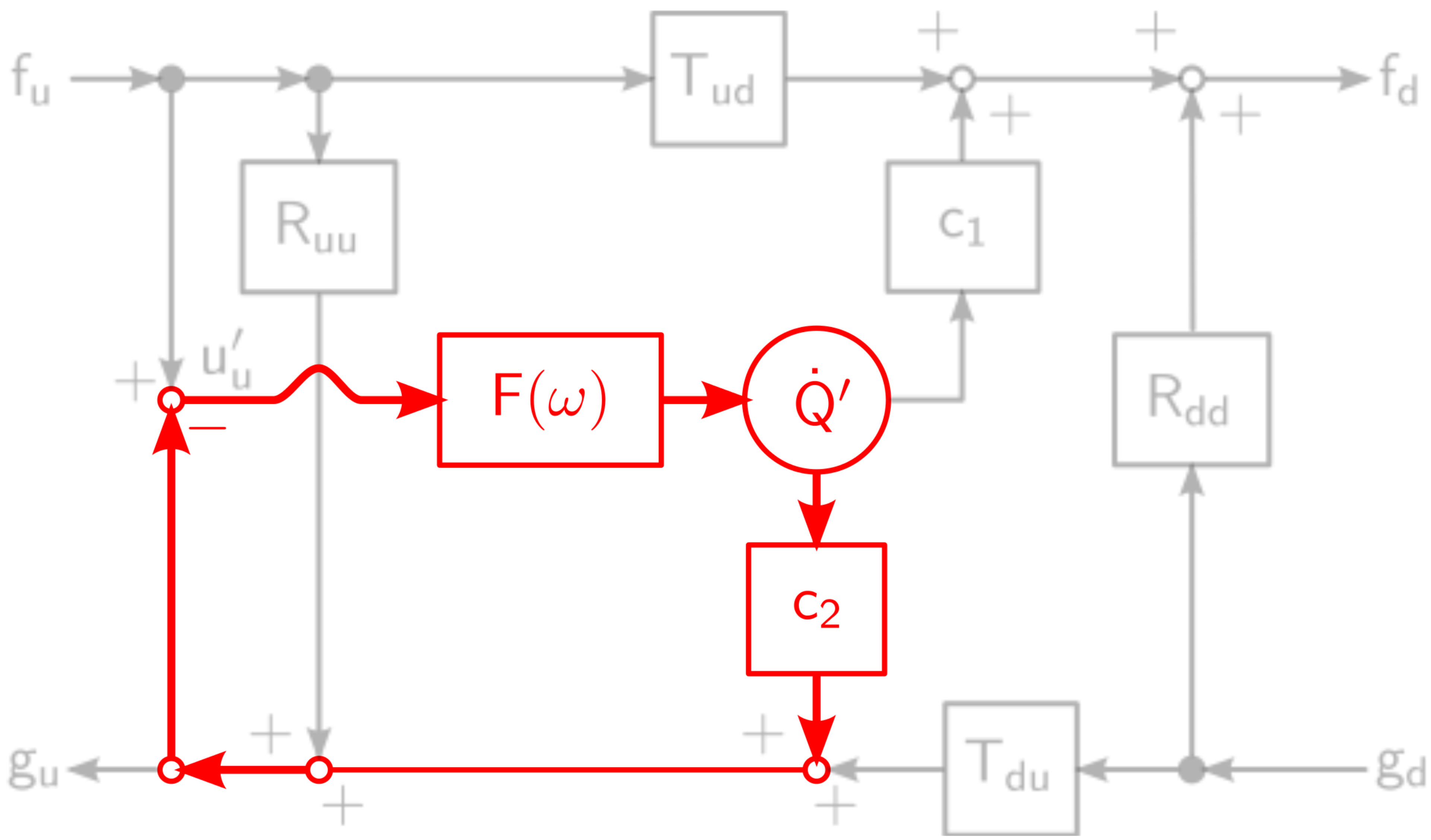
The complete set of thermoacoustic eigenmodes comprises cavity and ITA modes

ITA modes are characterized by a flip in u$'$ and $\nabla p'$ across the flame

ITA modes exhibit anomalous behaviour

ITA feedback explain paradoxical observations

TA analysis



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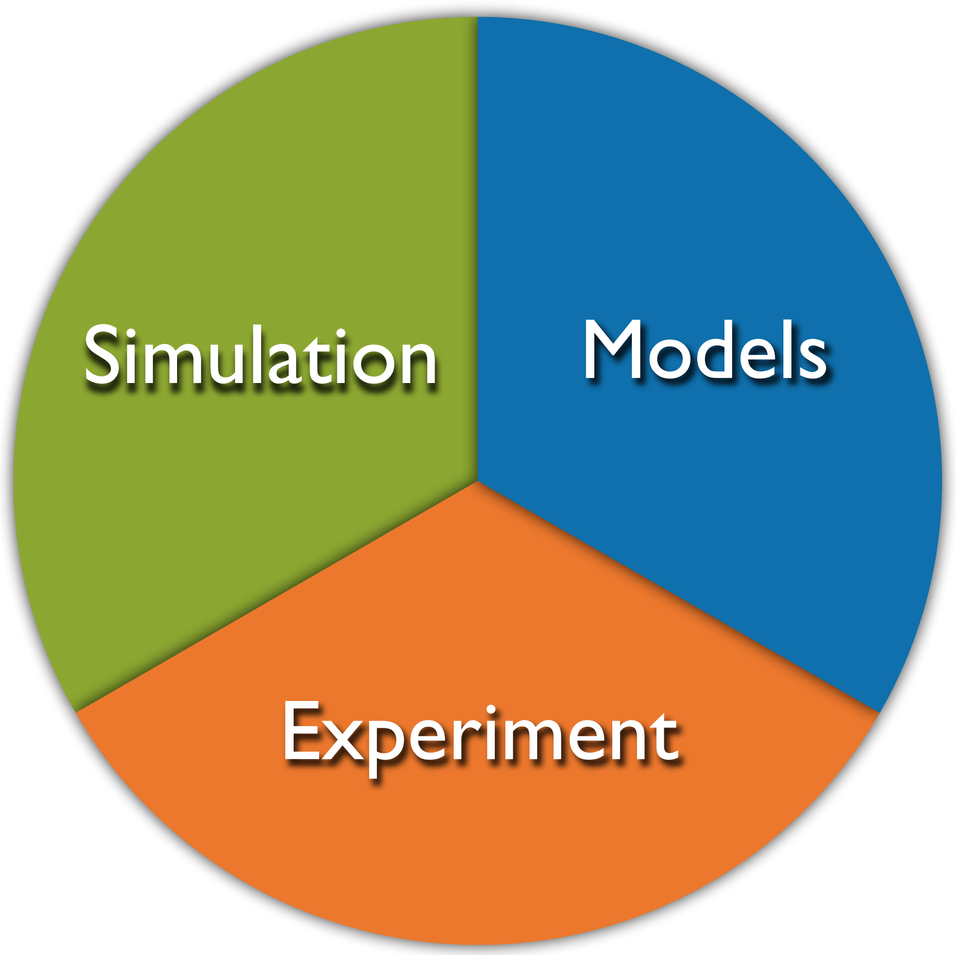
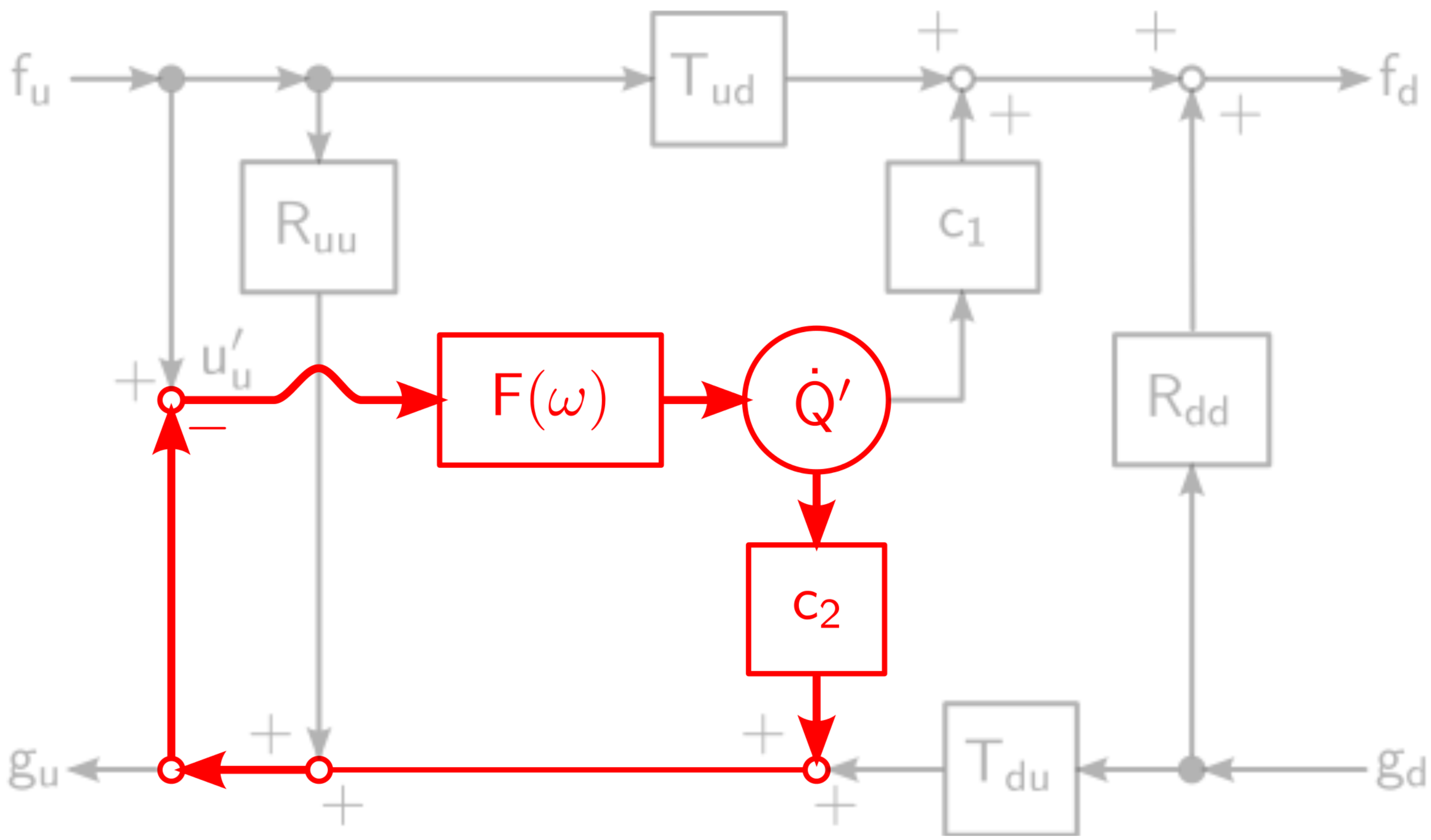
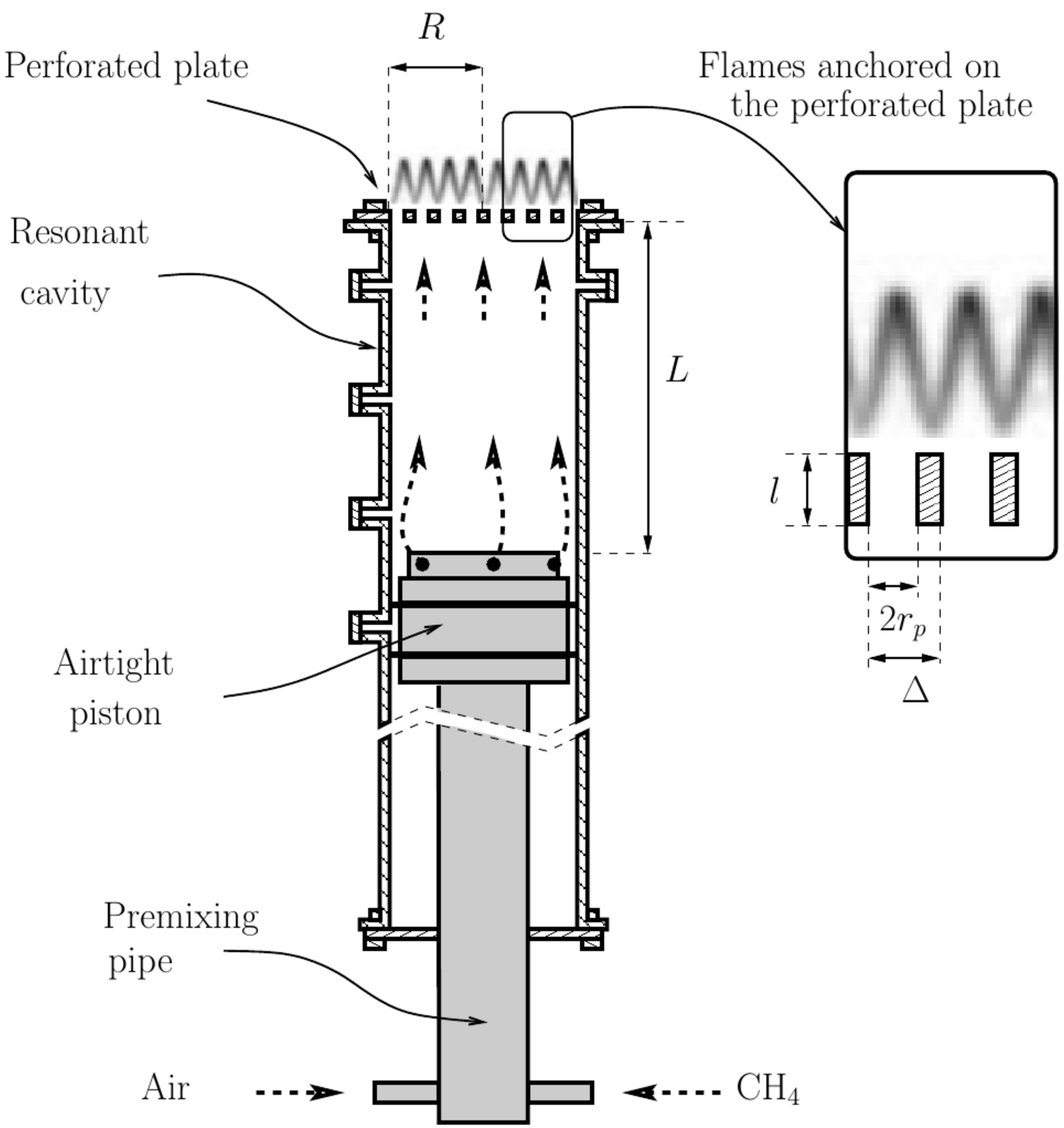
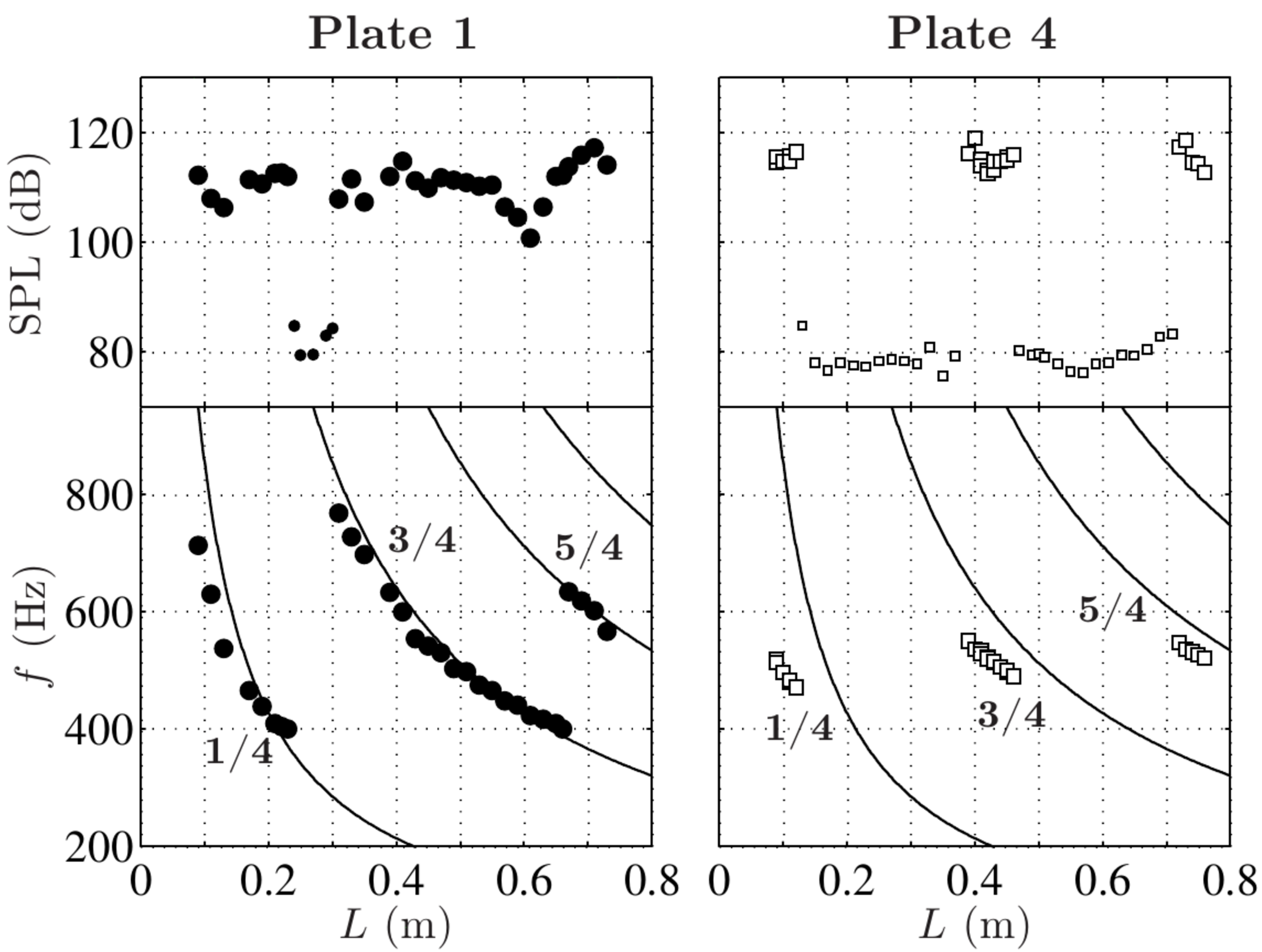




ITA feedback is important for instability / noise of open flames:
Plate 4 has high viscous losses; unstable only at ITA frequency ~ 500 Hz

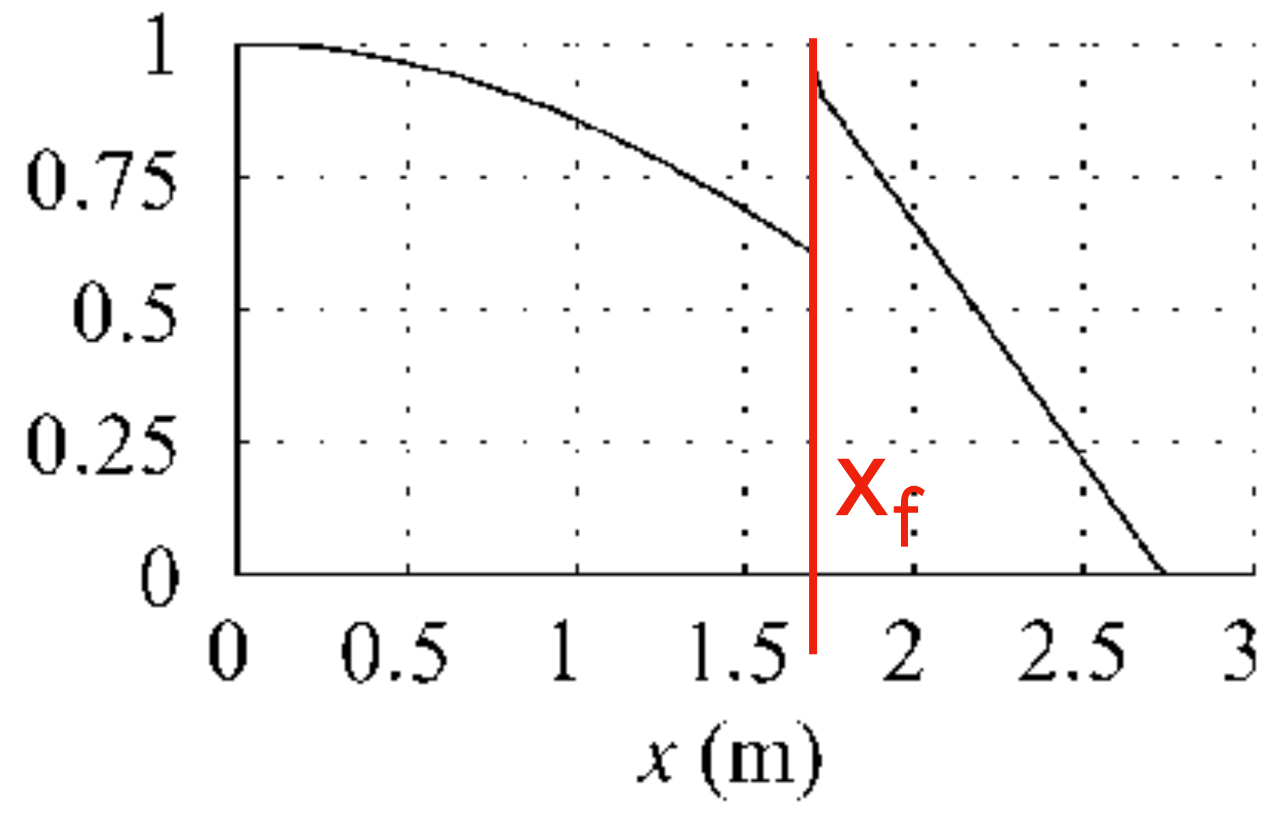




N. Noiray (2007)

Dowling and Stow (JPP, 2003) observed in a low-order model of a gas turbine modes „associated with flame model"

1/4 wave @ 30 Hz



ITA mode @ 168 Hz