The von Karman Institute
for Fluid Dynamics

UCL
Université
catholique
de Louvain

On The Dynamic Response of Constant Temperature Hot-Wire Anemometers (CTHWA)

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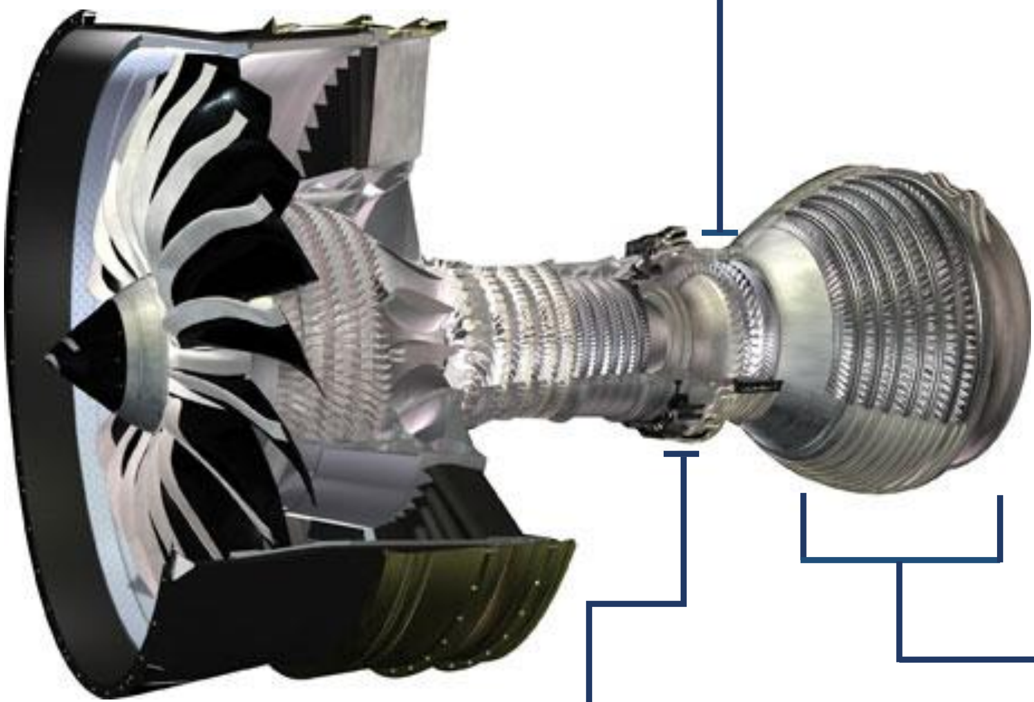
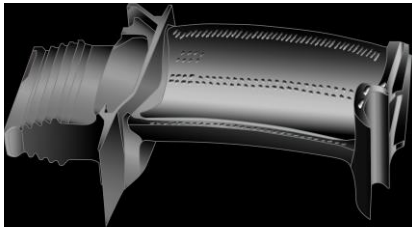
fnrs
FREEDOM TO RESEARCH

Context

CFM LEAP engine

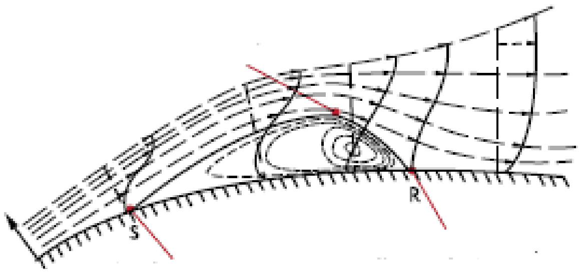


HP turbine
heat transfer



Turbulence effect in aero-engines

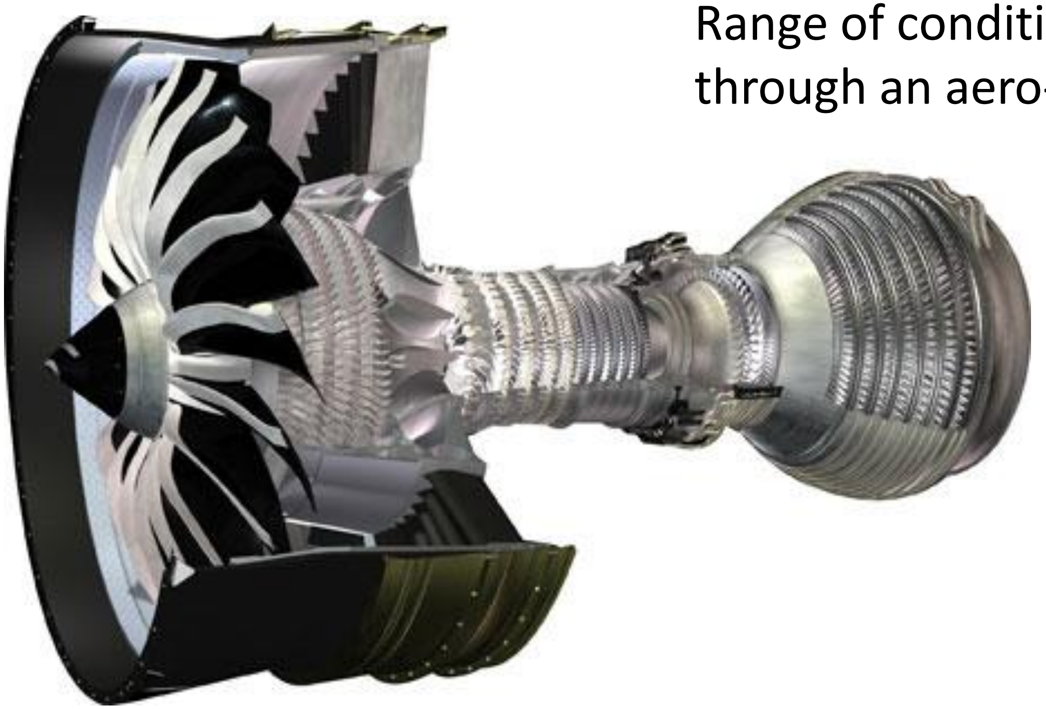
LP turbine
bl transition - separation



Combustion chamber
turbulence-chemistry interaction

Context

CFM LEAP engine



Range of conditions
through an aero-engine:

M: $0.1 \sim 1.2$

BPF: $1 \sim 15\ kHz$

Tu: $> 10\%$?

High speed flow
Unsteady phenomena
High turbulence level

Turbulence measurements
in turbomachinery flows:

High frequency response
High spatial resolution

Why CTHWA?

Constant Temperature Hot-Wire Anemometry (CTHWA)

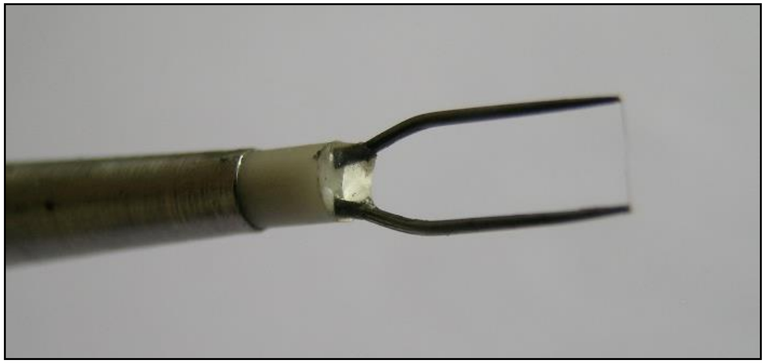
High spatial resolution:
$d_{wire} \sim 5 - 10\ \mu m$

High frequency response:
up to $60\ kHz$

→ *Basic research tool in turbulence*

TODAY'S PRESENTATION:

Investigation of the dynamic response of a CTHWA system



Why CTHWA?

Constant Temperature Hot-Wire Anemometry (CTHWA)

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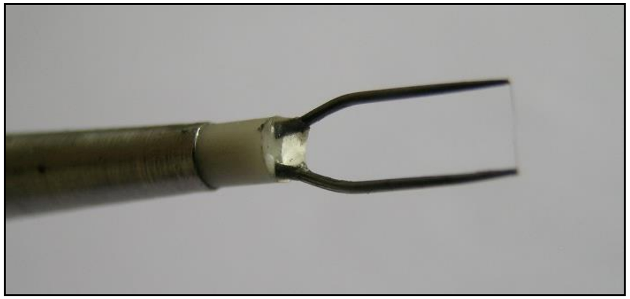
TODAY'S PRESENTATION:

Investigation of the dynamic response of a CTHWA system

→ *HWA is an established technique. What is left to investigate?*

CTHWA

CTHWA: probe + electronics



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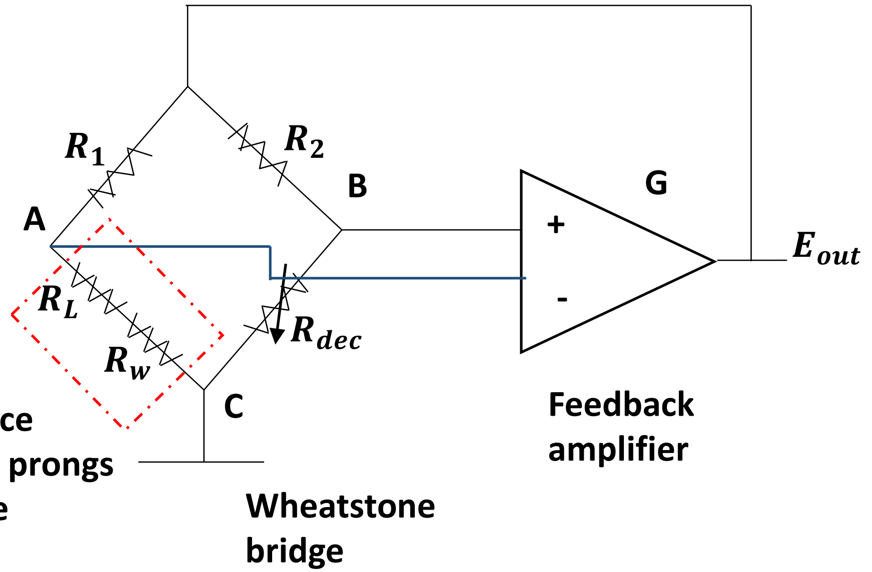
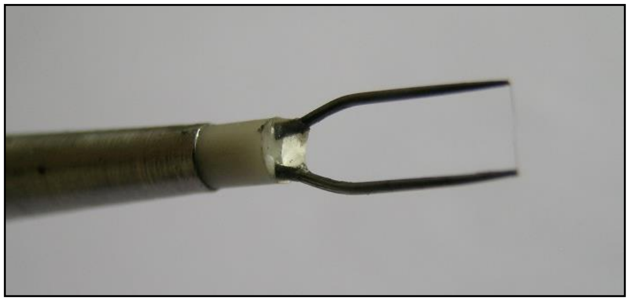
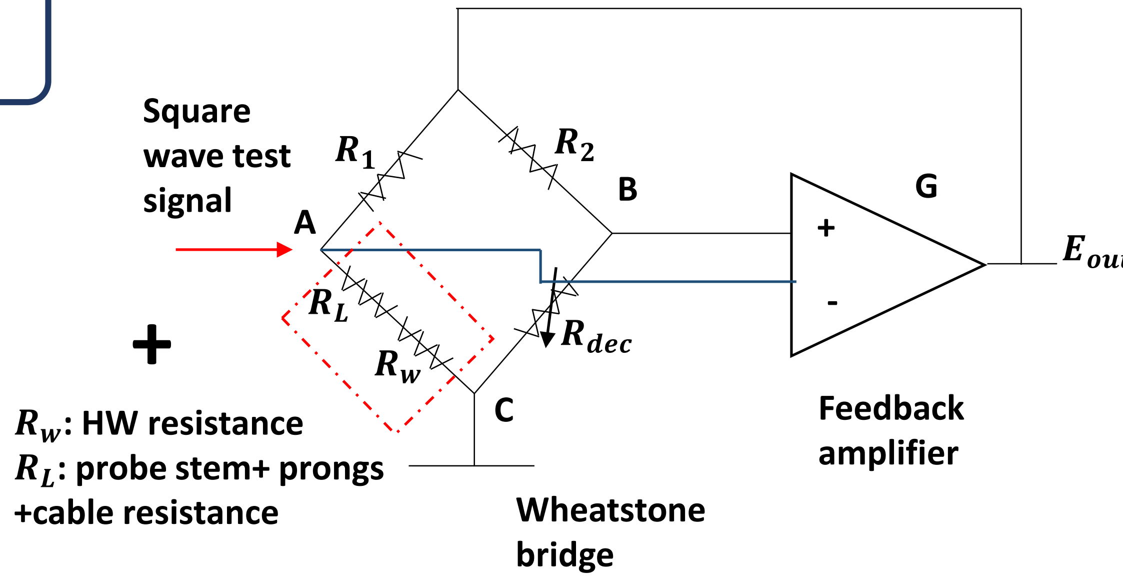


R_w: HW resistance
R_L: probe stem+ prongs +cable resistance

Square wave test

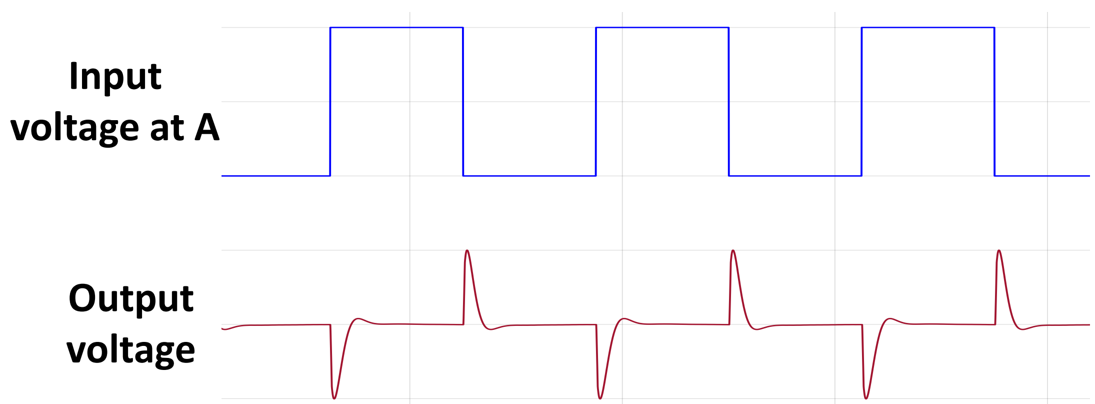
CTHWA: probe + electronics





Common method for dynamic response optimization:

“square wave test”



Square wave voltage perturbation

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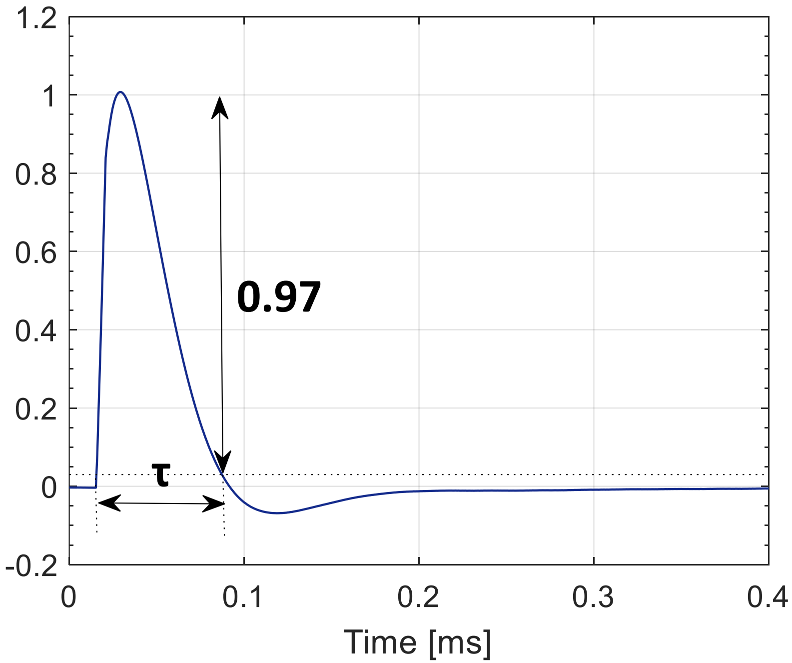
Velocity impulse perturbation

CTHWA typical use

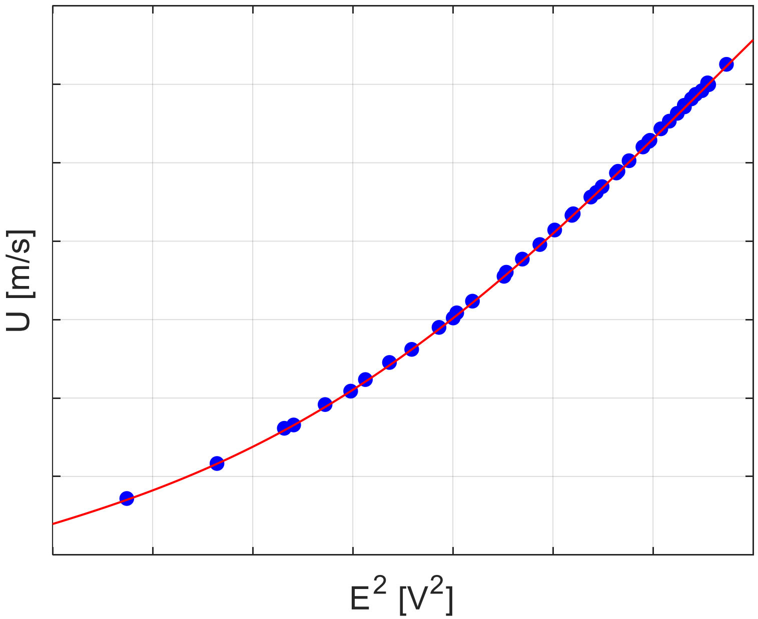
Optimized response to square wave



$$f_{cut} = \frac{1}{1.3\tau}$$: -3 dB attenuation

+

Static calibration



$$U = f(E^2)$$

Response assumed flat up to f_{cut}

Static calibration used

→ **Dynamic response effects neglected!**

In this work:

GOAL:

Highlight often neglected effects of the dynamic behavior of CTHWA on the measurement of turbulence

USING:

Numerical model + **Experimental square wave test**

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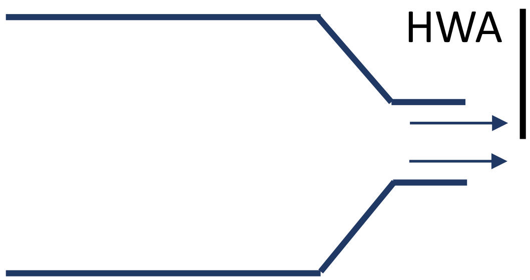
GOAL: *Highlight often neglected effects of the dynamic behavior of CTHWA on the measurement of turbulence*

USING: **Numerical model** **+** **Experimental square wave test**

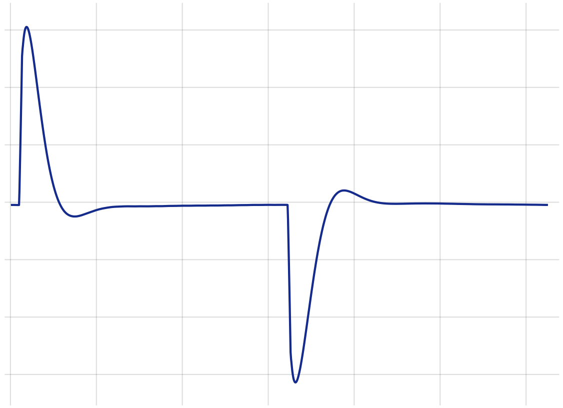
- Thermal transient effects due to heat conductions to the wire supports
- Non-linear effects important for large fluctuations
- Is the square wave test equivalent to the response to a velocity perturbation?

Experimental method



- HW probe placed in the flow (Response depends on the flow conditions)

- Using the embedded square wave voltage generator of the Dantec Streamline system, acquire the signal with $f_s = 1.25\ MHz$

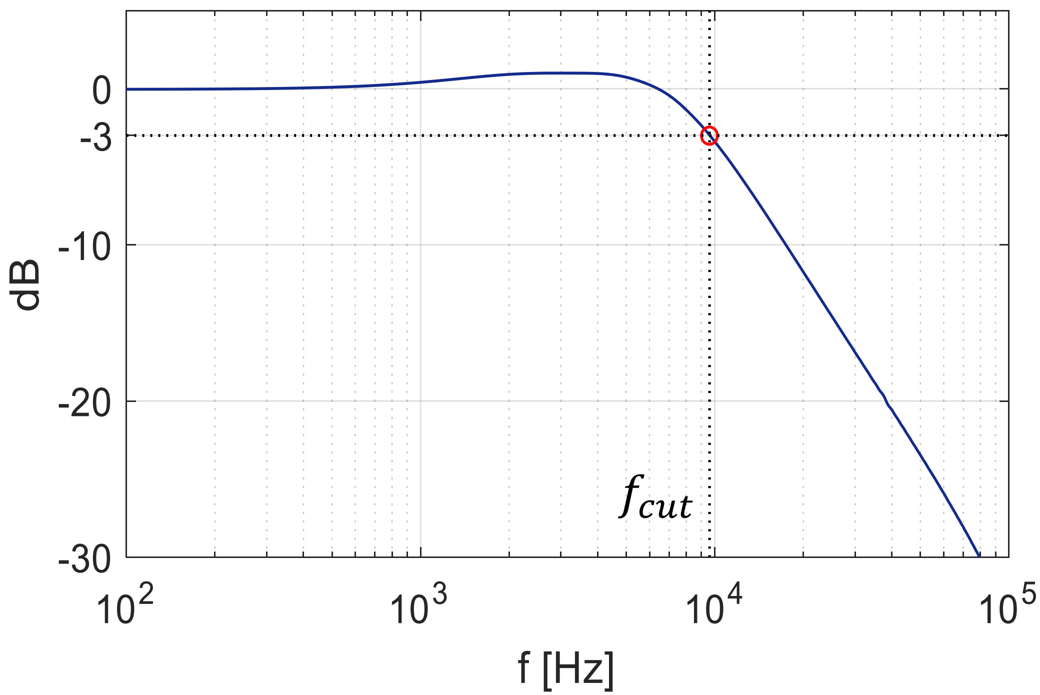


- Phase averaging to eliminate effect of flow fluctuations and obtain a clean signal

Experimental method

- Compute Fourier transform of averaged response

- System is a "black-box", unknown amplitude of input voltage



- To compute transfer function: Non-dimensionalization with amplitude at low frequency, where amplitude can assumed to be 1

Amplitude transfer function

Numerical model

Proposed by Freymuth (1977) & used by Weiss et al. (2013):

1. Wheatstone bridge equation:

$$\delta = \frac{R_1(R^* - R_w)}{(R_1 + r_L + R^*)(R_1 + r_L + R_w)} E + M_B \frac{dE}{dt} + \frac{R_1(r_L + R_w)}{(R_1 + r_L + R_w)} \frac{E_t}{R_t}$$

Term only present for the square wave test

2. Amplifier equation:

$$M'' \frac{d^2 E}{dt} + M' \frac{dE}{dt} + E = G\delta + E_B$$

3. Wire equation:

$$m_w c_w \frac{\partial T_w}{\partial t} = \frac{E^2 R_w}{(R_1 + r_L + R_w)^2} - Nu \pi l_w k_f (T_w - \eta T_0) - k_w A_c \frac{\partial^2 T_w}{\partial x^2}$$

heat conduction term

Convection losses term for non-dimensional calibration $Nu = f(Re)$

Numerical model

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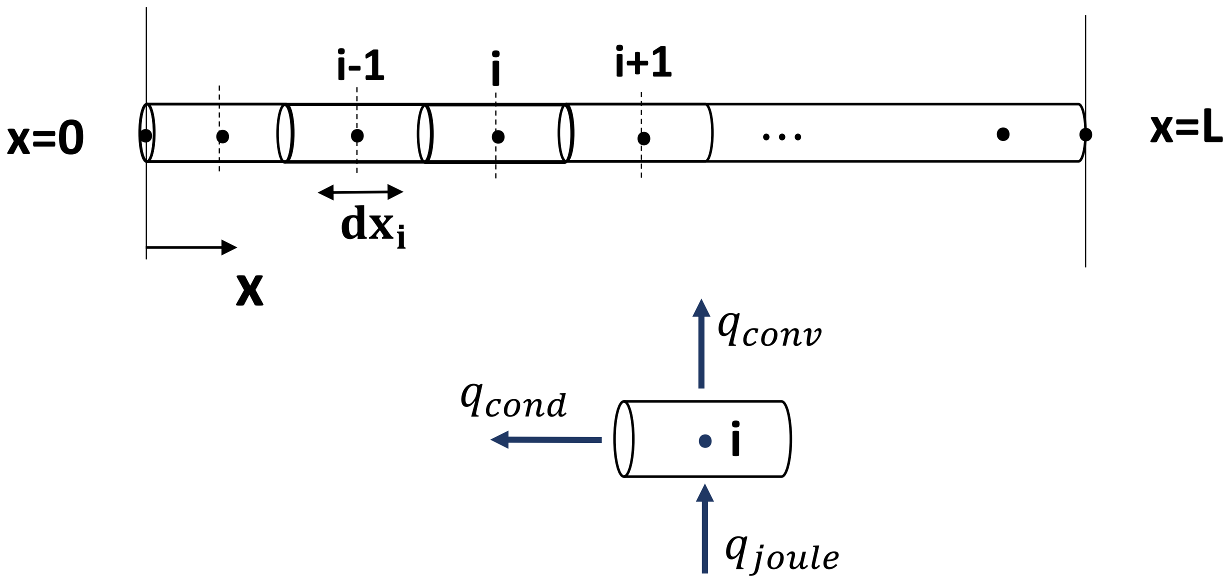
→ ***System of 2 ODEs and 1 PDE***

Numerical solution

- The wire is discretized in ***n-1*** elements and ***n*** nodes



- The spatial derivative is discretized and the wire equation is written for each node:

$$m_{w,i}c_{w,i}\frac{\partial T_{w,i}}{\partial t}=\frac{E^2R_{w,i}}{(R_1+r_L+R_{w,tot})^2}-Nu_i\pi l_i k_f\left(T_{w,i}-\eta \mathrm{T}_0\right)-\mathrm{k}_w A_{c,i}\frac{T_{w,i+1}-2T_{w,i}+T_{w,i-1}}{dx_i}$$

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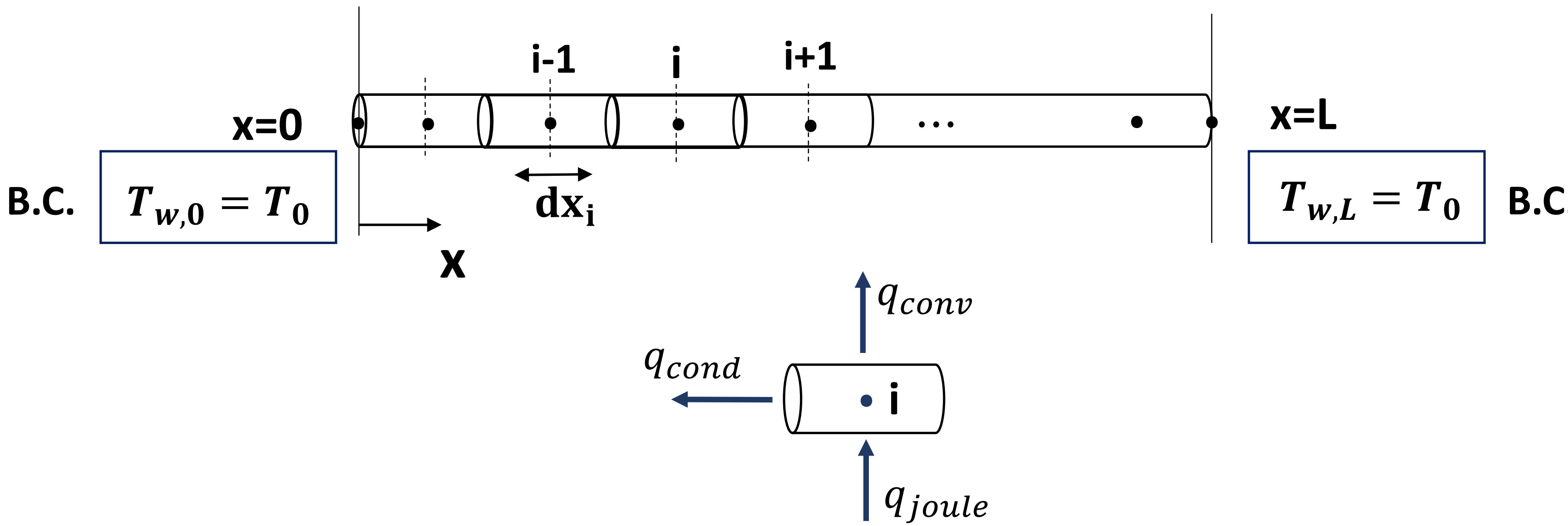

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System of n+2 ODEs

Solve with Runge-Kutta method

Numerical solution

Wire equation:

$$m_{w,i}c_{w,i}\frac{\partial T_{w,i}}{\partial t} = \frac{E^2 R_{w,i}}{(R_1 + r_L + R_w)^2} - Nu_i \pi l_i k_f (T_{w,i} - \eta \mathrm{T}_0) - \mathrm{k}_w A_{c,i}\frac{T_{w,i+1} - 2T_{w,i} + T_{w,i-1}}{dx_i}$$

→ Temperature profile along the wire at each time instant

T_w spatial average and corresponding R_w

$$T_w = \frac{1}{L}\int_0^L T_w(x)\,dx$$

$$R_w = R_{ref}(1 + a_w(T_w - T_{ref}))$$

Input to ↓

Wheatstone bridge equation:

$$\delta = \frac{\mathrm{R}_1(R^* - R_w)}{(R_1 + r_L + R^*)(R_1 + r_L + R_w)}E + M_B\frac{dE}{dt} + \frac{\mathrm{R}_1(r_L + R_w)}{(R_1 + r_L + R_w)}\frac{E_t}{R_t}$$

Circuit parameters' estimation

Commercial system used, certain circuit parameters are not know:

$$\boldsymbol{G, M', M'', E_b, M_B}$$

- E_b, offset voltage of the amplifier. No adjustment in our system. Increases the damping of the system, a constant high value is selected following Perry (1972).

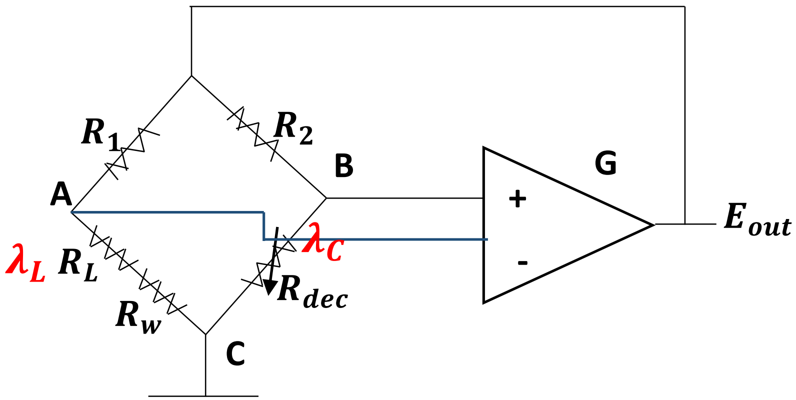
$$E_b = 5\ V$$

- M_B, bridge time constant takes into account high frequency components. It is adjusted by varying an inductance λ_L of a set of coils to compensate for the inductance of the cable λ_C (Freymuth 1977),

$$M_B = \frac{\lambda_L/\mathrm{R}_2 - \lambda_C/\mathrm{R}_1}{(n+1)^2} = 10^{-10}$$

- G, amplifier gain. Adjusted during square wave test.

- $\boldsymbol{M', M''}$time constants of the amplifier. Adjusted during square wave



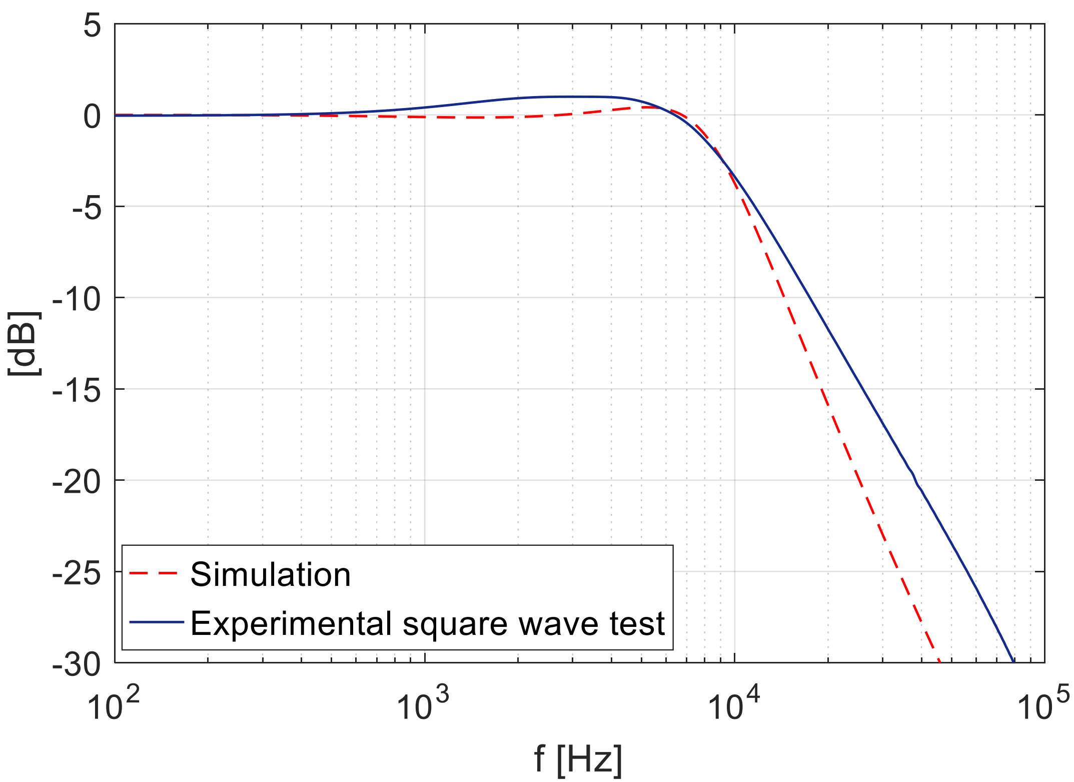
Comparison with experiments

Comparison of the model with experimental square wave test

Tungsten wire
$d_w = 9\ \mu m$
$l_w = 1mm$
$T_w = 455\ K$
M=0.25

$G = 230$
$M' = 1.6 \cdot 10^{-5}$
$M'' = 10^{-11}$

→ To predict the same f_{cut}



- Steeper attenuation at high frequencies
- Different behavior at low frequencies

Further investigation required!

In this work:

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- Thermal transient effects due to heat conductions to the wire supports
- Non-linear effects important for large fluctuations
- Is the square wave test equivalent to the response to a velocity perturbation?

Velocity vs voltage perturbation

Voltage perturbation "square wave test"	❖ Electronic testing ❖ Common method to test dynamic response
Velocity (Reynolds) perturbation	❖ Direct testing ❖ Real case ❖ Difficult to perform

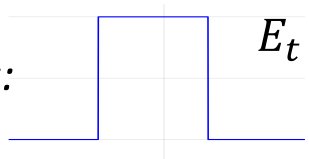
The square wave test should be always used to adjust the response and avoid a self-oscillating system

BUT can it be used as a reliable estimation of the system's response?

↓

Disagreement in literature

Use the model to simulate both cases:

- *Case1, Inputs:* 

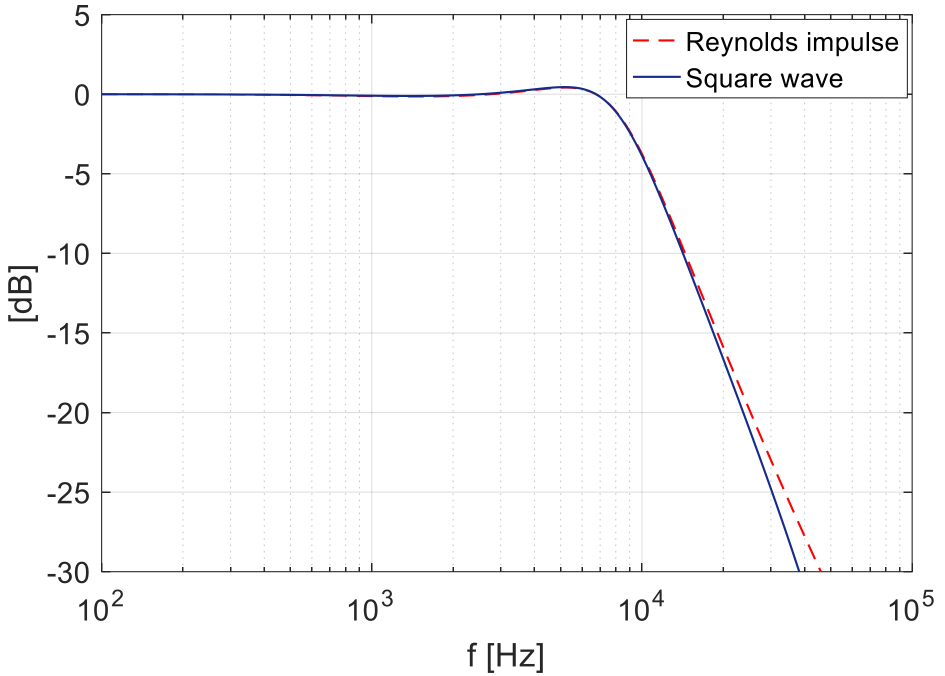
$Re = const$

- *Case2, Inputs:* 

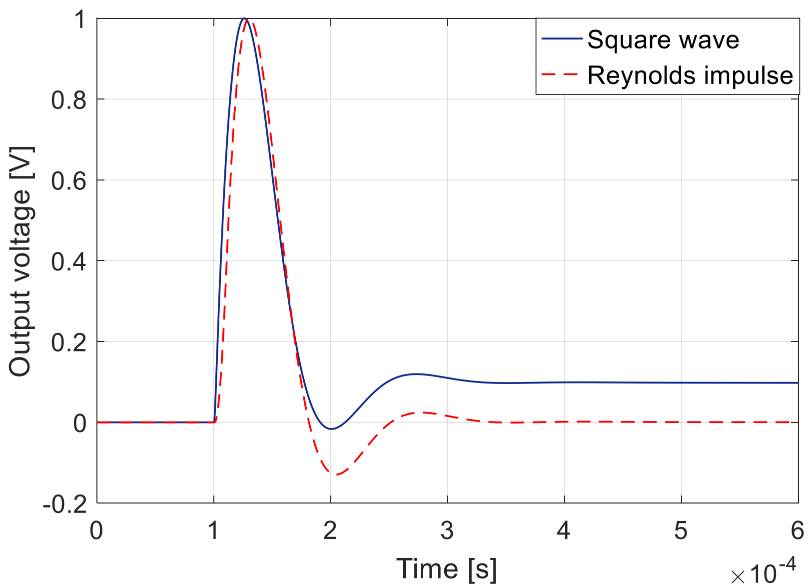
$E_t = 0$

Velocity vs voltage perturbation

Compare response to square wave voltage and response to Reynolds impulse



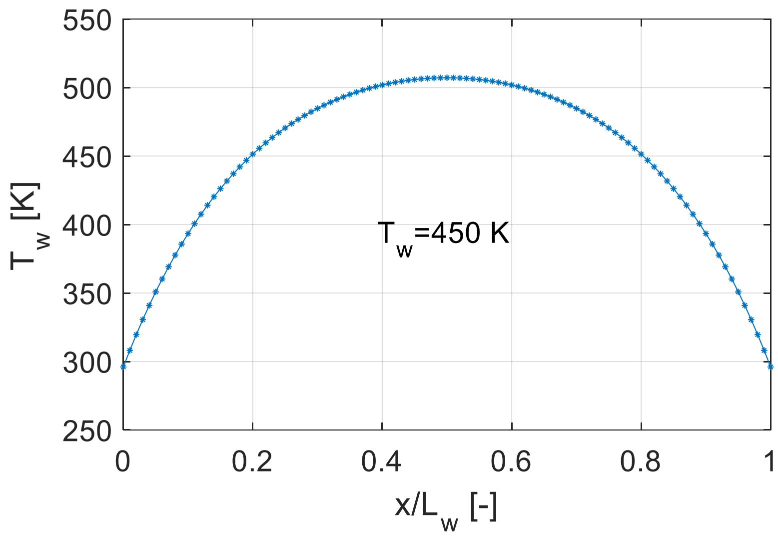
Only difference at high frequencies



Square wave seems to simulate adequately Reynolds impulse

Transfer function could be used to correct amplitude

Thermal transient effects

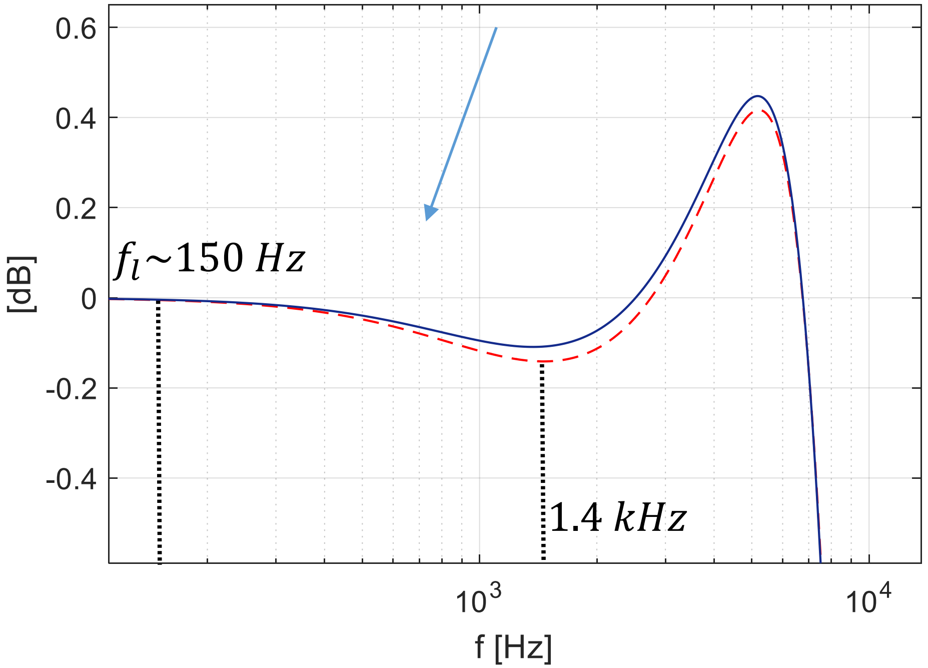


Temperature profile along the wire

$$T_w = 450\ K$$

$$T_{w,exp} = 455\ K$$

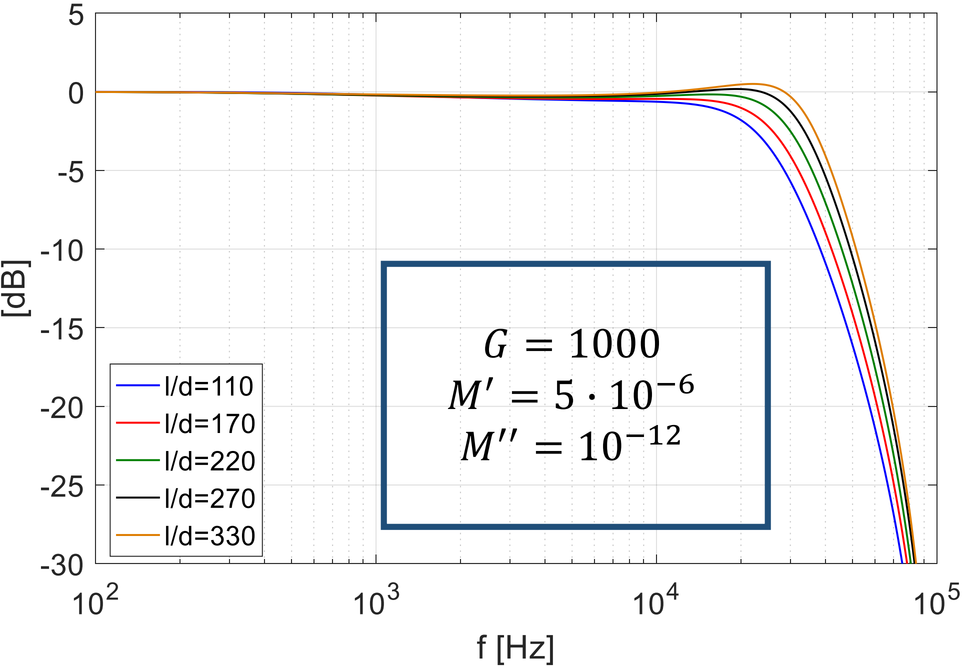
Square wave response also features attenuation



Low frequency attenuation due to heat conduction to the wire supports from $f_l \sim 150\ Hz$

From $f > 1.4\ kHz$ amplification due to system dynamics, attenuation not completed

Thermal transient effects



Adjust amplifier parameters to move cut-off to higher frequencies

→ **Focus on attenuation**

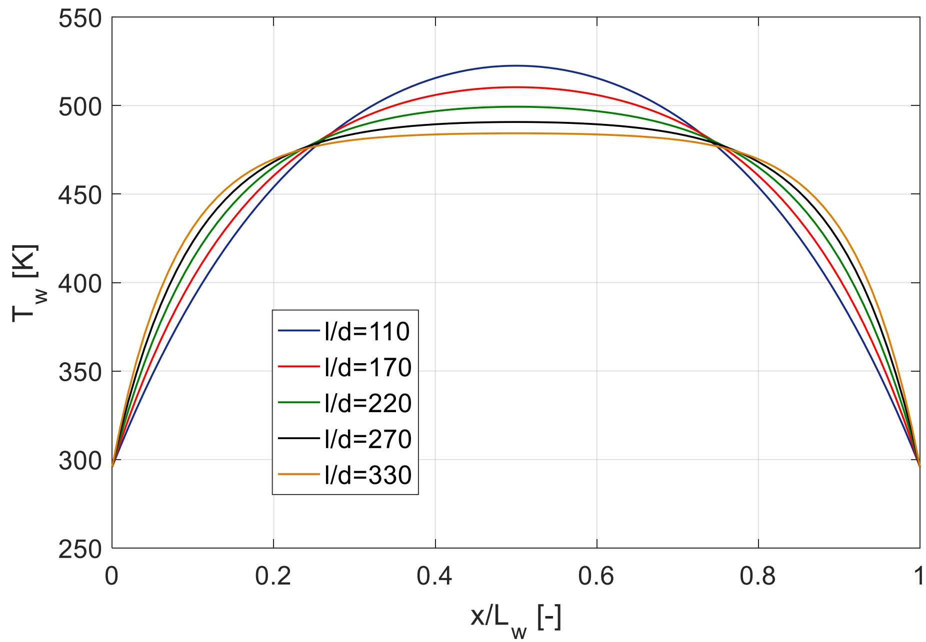
l/d ratio effect

High l/d

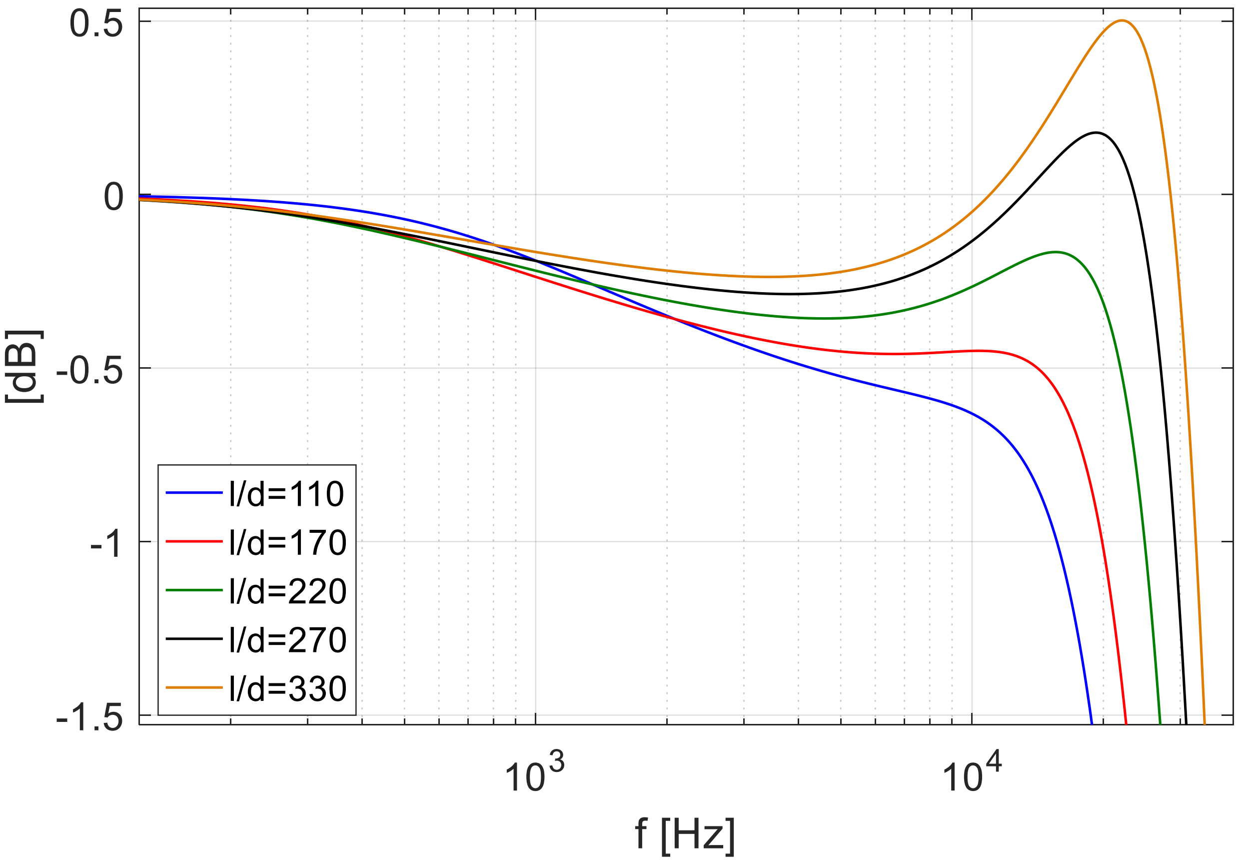
↓

convection > conduction

Flatter T_w disribution



Thermal transient effects



High l/d

Final attenuation value decreases

High *l/d* should be used for less attenuation

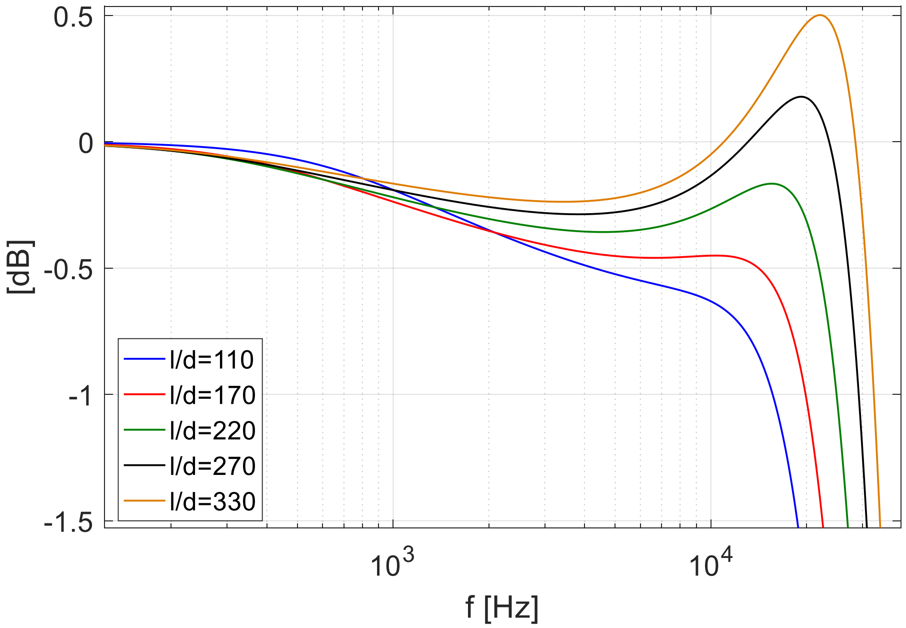
Small *l* should be used for spatial resolution

Min *d* restricted by mechanical strength

Trade-off

Choice depends on application

Thermal transient effects

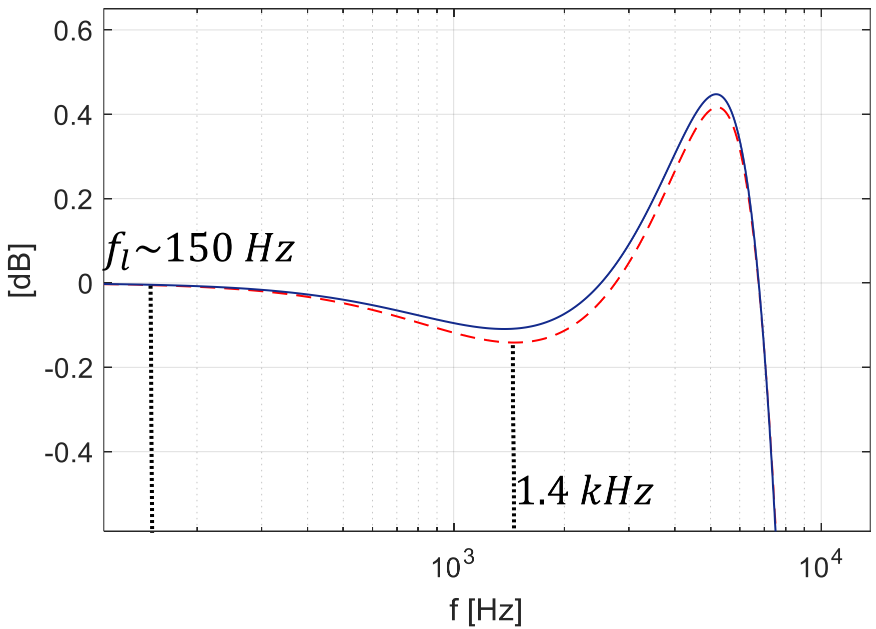


Attenuation important for a wide range of frequencies even for l/d=330

Correction should be applied

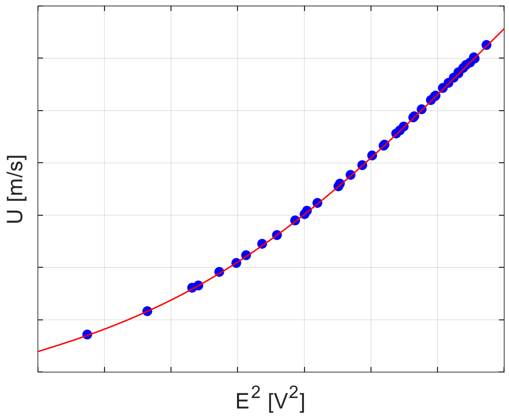
Attenuation also present at square wave test response, negligible difference

Square wave transfer function could be used for correction



Non-linearity

The response of CTHWA is non-linear



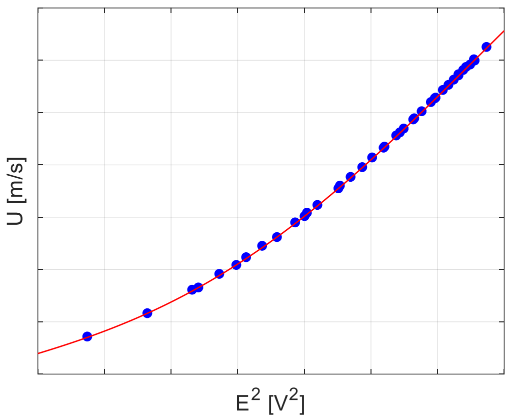
Non-linear static response
heat transfer law

+

Non-linear dynamic response
Bridge and wire equations of the dynamic model

Non-linearity

The response of CTHWA is non-linear



Non-linear static response
heat transfer law

Corrected with calibration

+

Non-linear dynamic response
Bridge and wire equations of the dynamic model

Usually neglected

Valid for small fluctuations

Errors for large fluctuations

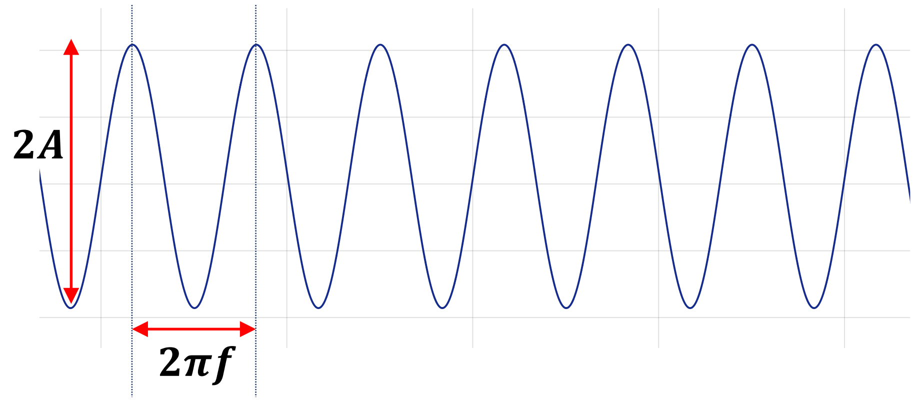
Turbomachinery flows!

Errors mainly affect odd turbulence moments, e.g. skewness

Non-linearity

Reynolds input to the model:

$\boldsymbol{Re_{in}}$



Static calibration

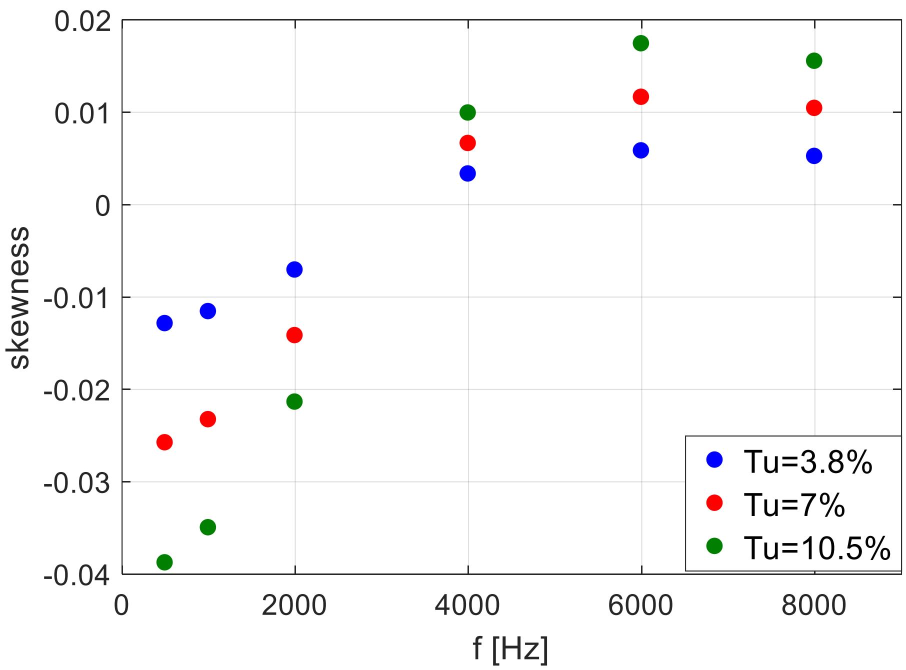
Output voltage → Output Reynolds $\boldsymbol{Re_{out}}$

Skewness of $\boldsymbol{Re_{out}}$

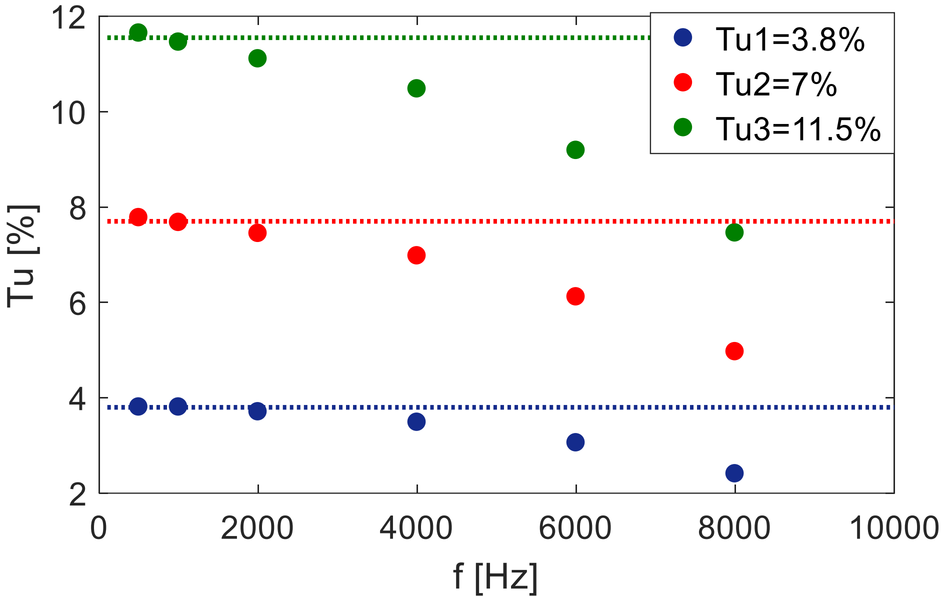
↓

Increasing with increasing amplitude

Results agree with Weiss et al. (2013)



Non-linearity



For increasing frequency:

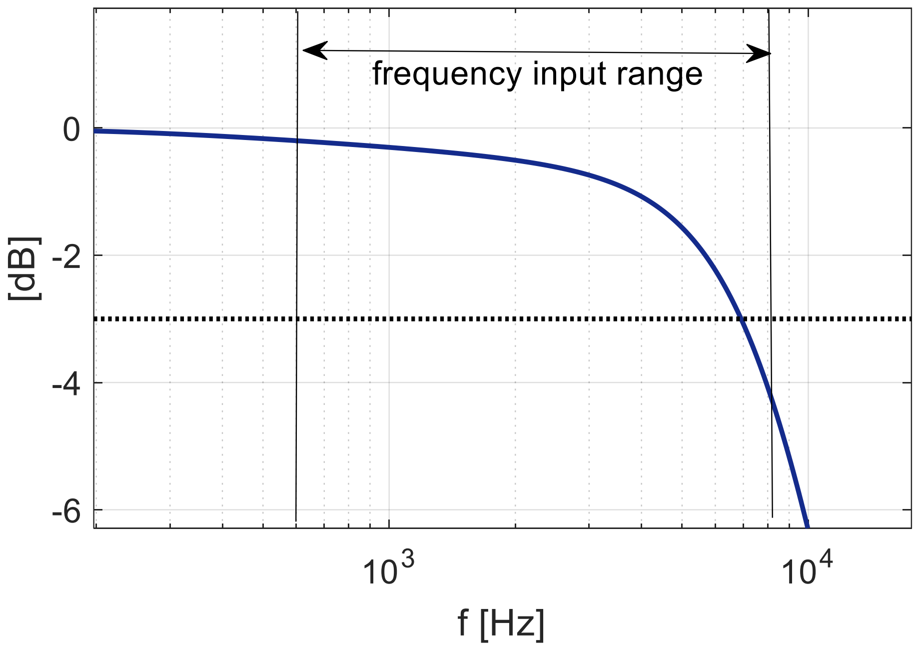
$$T_{u,out} < T_{u,in}$$

Range of input frequencies affected by attenuation

Heat conduction attenuation +system damping

Significant attenuation

Correction should be applied!



Conclusions

- Identification of possible sources of errors in turbulence measurements due to the dynamic response of CTHWA :
  - Attenuation due to heat conduction
  - Amplification or damping due to system dynamics
  - Non-linearity errors

- For small fluctuations, the first two could be corrected by applying a transfer function to the measured spectrum. According to this model, the transfer function obtained with the square wave test could be used but further validation is required.

- For large fluctuations the effect of non-linearity can have a significant effect on the skewness. It can not be corrected by a transfer function. Correction method existing for Constant-Voltage-Anemometry (Berson et al. 2009) but not for CTHWA.

Future work

- Further work on the validation of the dynamic model:
  - Use a VKI anemometer instead of a Dantec system to better estimate the circuit parameters
  - Consider direct testing (eg by laser heating) in addition to the electronic testing
- Further work on the possibility of corrections.
- Use of the model for the design of HW probes with optimized response
- Investigate spatial resolution issues

References

- P. Freymuth, (1977), Further Investigation of the Nonlinear Theory for Constant-Temperature Hot-Wire Anemometers, Journal of Physics E: Scientific Instruments 10.
- J. Weiss, A. Berson, G. Comte-Bellot, (2013) Investigation of Non- Linear Effects in Constant Temperature Anemometers, Measurement Science and Technology 24.
- A. Berson, P. Blanc-Benon, G. Comte-Bellot, (2009), A Strategy to Eliminate All Nonlinear Effects in Constant-Voltage Hot-Wire Anemometry, Review of Scientific Instruments 80.
- A. E. Perry, G. L. Morisson, (1971) A Study of the Constant- Temperature Hot-Wire Anemometer, Journal of Fluid Mechanics 47 (3).

Thank you for your attention!