FREQUENCY ENHANCEMENT OF DUAL-JUNCTION THERMOCOUPLE PROBES

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ABSTRACT

This paper presents a numerical procedure to enhance the frequency response of temperature probes equipped with two thermocouple junctions of different diameter. The thermocouple behavior under transient conditions is bounded to frequencies below a few Hertz. The main factor limiting the frequency bandwidth is the unsteady conduction along the wire. In this research, the output of the two thermocouples exposed to the same flow transient is used to predict the output of a finer modelled thermocouple. The resulting modelled fine wire thermocouple had a cut-off frequency that was one order of magnitude higher than the physical junctions. The numerical procedure was demonstrated to recover the response to a step in temperature and the maximum error between the compensated and the theoretical signal was below 1%.

NOMENCLATURE

P: pressure [Pa]
T: Temperature [K]
$\bar{T}$: Fourier Transform of the temperature signal
U: velocity [ms^{-1}]
d: wire diameter [m]
FFT: Fast Fourier Transform
f: Hertz [s^{-1}]
NS: Navier-Stokes
M: Mach number [-]
Z: Overall recovery factor [-]

INTRODUCTION

Thermocouples are the preferred technique to monitor temperature in turbomachinery due to the superior accuracy and reliability, however their frequency response is restricted below a few Hz [1, 2]. In particular, the slow conduction from the wire to the support prevents a precise evaluation of the transients.

The velocity error and the steady conduction error have been traditionally evaluated experimentally [3, 4]. Based on the theoretical model of Yule et al. [5], Petit et al. [6] also studied the unsteady behavior of the thermocouple and the influence of the wire geometry.

Villafane and Paniagua [2] performed transient full conjugate simulations to quantify steady state loss sources and transient temperature effects when the thermocouple is subjected to unsteady flowfield.

Forney and Fralick [7] presented an analytical method for a dual wire thermocouple. This allowed for an expression of the gas temperature that was only function of the temperature sensed by the individual thermocouples and the wire diameters.

In the current paper, we first describe the design procedure to model the thermocouples with solid-fluid conjugate simulations, followed by the description of the digital compensation. The procedure is eventually applied to predict the unsteady response of a theoretical fine wire thermocouple exposed to a temperature step.

STEADY STATE PERFORMANCE

Bare thermocouples of type K were investigated, with a l_{wire} /d_{wire} of 10 and three diameters of 12.5, 25 and 50 micrometer. For the three cases the bead of the thermocouple was 2.5 times the diameter of the wire and the properties of the bead were 50 % Alumel and 50 % Chromel. The properties are given in Table 1. The 3D RANS simulations were performed with CFD ++ of Metacomp [8]. The numerical domain was a structured mesh and consisted of 2.6 million cells around the bare thermocouple displayed in Figure 1-right. The simulations were parallelized on 8 HP compute nodes. To account for heat transfer from the fluid to the thermocouple and stem, the simulations were carried out with the conjugate heat transfer model, coupling the Fourier heat equation in the solid domain with the NS- equations in the fluid domain. The amount of cells in the wire and bead of the thermocouple was around 0.3 million cells. The k-epsilon turbulence model was used to solve the Reynolds' stresses. In all simulations y+ was kept below one to ensure that the laminar sublayer was correctly resolved. At the inlet of the domain, a velocity of 150 m/s and a static pressure of 1 bar were imposed. Three different inlet static temperature were considered: 300 K, 400 K and 500 K. At the outlet, a static pressure of 1 bar was applied. The thermocouple support was modeled as an isothermal wall at 300 K. The average surface temperature of the bead corresponded to the reference temperature of the thermocouple junction.

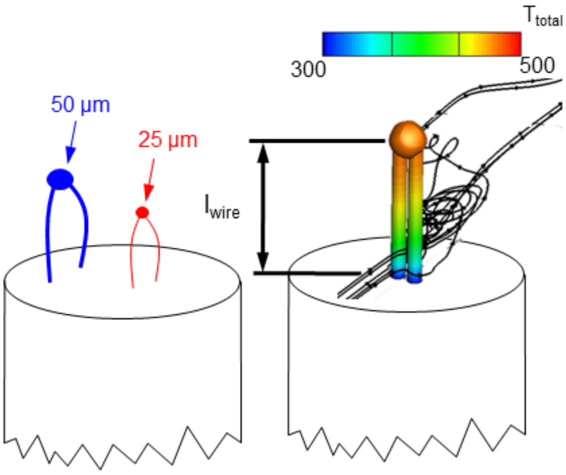

Figure 1: Left: dual-junction thermocouple. Right: numerical domain of the thermocouple.

	K [W m^-1 K^-1]	*ρ*C_p [kg m^-1 s^-2 K^-1]*
Wire 1	*30*	*4.08*10^3*
Wire 2	*19*	*3.29*10^3*
Bead	*24.5*	*3.69*10^3*

Table 1: parameters for the K-type thermocouple

We performed nine different steady simulations for the three thermocouples. To retrieve the total temperature of the flow to which the thermocouple is exposed, we define the overall recovery factor which relates the temperature at the junction to the total temperature and the difference between static and total temperature:

$$Z = 1 - \frac{T_0 - T_{junction}}{T_0 - T_{static,\ inlet}}$$

(Eq. 1)

The overall recovery factor is influenced both by the Mach number, the Reynolds number and l_{wire}/d_{wire} [1, 2]. Figure 3 plots the recovery factor at three different Mach numbers (where the inlet static temperature of 300 K corresponds to M=0.43, 400 K to M= 0.37 and 500 K to M=0.33). Interestingly, we observe that for the three thermocouples, the overall recovery factor reaches negative values for lower Mach number demonstrating that the junction temperature is below the static temperature of the flow field. This is a result of the conduction error at low l_{wire}/d_{wire} where $\frac{T_{junction} - T_{stem}}{T_{total} - T_{stem}}$ is up to 0.7 [1].

Second, we observe that the decrease of the wire diameter results in a decrease of the total recovery factor for a certain Mach number (as low as -7.4 for the 12.5 µm thermocouple), because of the decreased convective heat transfer across the wires for smaller diameter thermocouples. The overall recovery factor is used to compensate for the steady conduction and velocity error.

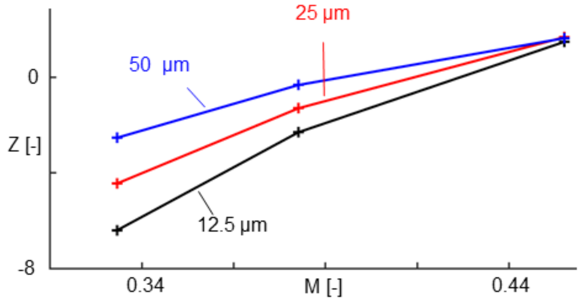

Figure 2: Overall recovery factor for the three thermocouples as function of the Mach number.

TRANSFER FUNCTION OF MULTIWIRE THERMOCOUPLES

We used the steady simulation with an inlet static temperature of 300 K as initial solution for the unsteady RANS simulations, where we imposed a step in the static temperature of 200 K at the inlet. Figure 2 represents the result of this unsteady simulation and shows the average total temperature on the bead of the thermocouple in function of time. For the three cases, the final junction temperature sensed by the thermocouple bead at t=0.05 ms is lower when the wire diameter is reduced. We also observe that the large thermocouple (50 µm) needs approx. 0.05 s to achieve steady state while this is approx. 10 times smaller for fine wire thermocouple of 12.5 µm. The sampling frequency was 10 kHz for all cases.

Based on the time response, the cut-off frequency of the 50 µm diameter thermocouple is 15 Hz, the cut-off frequency for the 25 micrometer diameter thermocouple is 50 Hz and 150 Hz for the 12.5 µm diameter thermocouple, demonstrating the higher frequency response for smaller diameters.

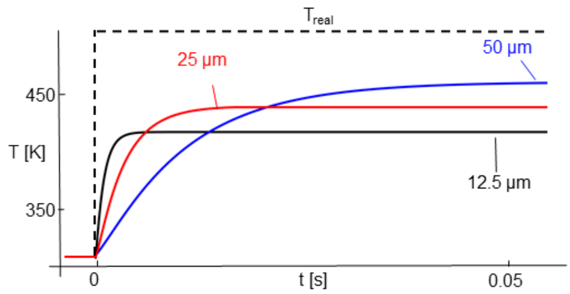

Figure 2: Time evolution of three thermocouple probes

Based on the method of Forney and Fralick [7], who assumed a first order response for the thermocouple, we propose a method to use the dual wire thermocouple (with diameters 25 µm and 50 µm, Figure 1-left) to retrieve the theoretical signal of a fine wire thermocouple (12.5 µm) with a frequency response up to 150 Hz. Figure 4 depicts the three ratios of FFTs in the frequency domain. The black curve represents the ratio of the 50 µm thermocouple signal to the 25 µm thermocouple signal, obtained from the dual-junction thermocouple. The blue and red curve represent the ratio of 50 µm thermocouple to the fine wire thermocouple (12.5 µm) and the 25 µm thermocouple to the fine wire, these two theoretical ratios are determined numerically. Due to the higher difference in wire diameter, $\frac{\bar{T}_{50\ \mu m}}{\bar{T}_{12.5\ \mu m}}$ displays higher difference than $\frac{\bar{T}_{25\ \mu m}}{\bar{T}_{12.5\ \mu m}}$, especially at frequencies below 200 Hz.

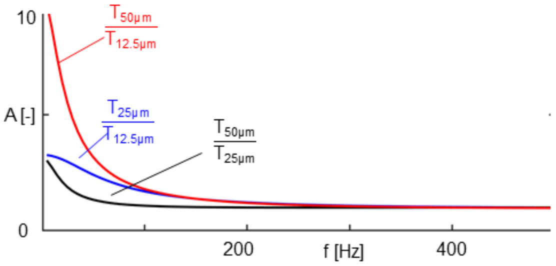

Figure 4: Transfer function ratios for the three thermocouples.

For the digital compensation, we propose a fourth order polynomial fitting to relate the black curve ($\frac{\bar{T}_{50\ \mu m}}{\bar{T}_{25\ \mu m}}$) to the red blue curve ($\frac{\bar{T}_{25\ \mu m}}{\bar{T}_{12.5\ \mu m}}$):

$$\frac{\bar{T}_{25\ \mu m}}{\bar{T}_{12.5\ \mu m}} = a\left(\frac{\bar{T}_{50\ \mu m}}{\bar{T}_{25\ \mu m}}\right)^4 + b\left(\frac{\bar{T}_{50\ \mu m}}{\bar{T}_{25\ \mu m}}\right)^3 + a\left(\frac{\bar{T}_{50\ \mu m}}{\bar{T}_{25\ \mu m}}\right)^2 + d\left(\frac{\bar{T}_{50\ \mu m}}{\bar{T}_{25\ \mu m}}\right)^4 + e$$

(Eq. 2)

Figure 5 plots the results of the fit in a range of 0 to 500 Hz with the original curve (in blue) and the estimated ratio with the applied curve fitting (black plus marks). The discrepancy between the estimated value and the original curve was below 1.1 %. The coefficients of the fourth order polynomial fitting are given in Table 2.

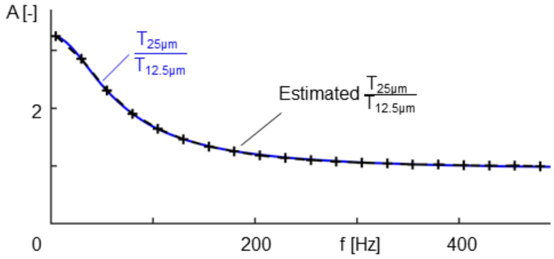

Figure 5: Transfer functions between the 12.5 µm and 25 µm thermocouple.

a	*0.0641 - 0.1147i*
b	*-0.1169 + 1.2811i*
c	*-1.6542 - 4.6768i*
d	*6.5683 + 6.7457i*
e	*-3.8779 - 3.2904i*

Table 2: Curve fitting coefficients for the 25 µm thermocouple.

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This method was assessed by recovering the theoretical response of the 12.5 µm thermocouple to a step in temperature of 200 K with our dual-junction thermocouple probe (with wire diameter of 25 µm and 50 µm). We use the overall recovery factor to obtain the true total temperature. After calculating the FFT of the dual wire thermocouple and applying the polynomial fitting with Eq. 2 and the coefficients of Table 2, we retrieve the estimated ratio of the of the fine wire thermocouple to the 25 µm thermocouple, $\left(\frac{\bar{T}_{12.5\ \mu m}}{\bar{T}_{25\ \mu m}}\right)_{estim.}$. We obtain the compensated FFT of the fine wire thermocouple by using the original FFT of the 25 µm thermocouple:

$$\bar{T}_{12.5\ \mu m,comp.} = \bar{T}_{25\ \mu m} \cdot \left(\frac{\bar{T}_{12.5\ \mu m}}{\bar{T}_{25\ \mu m}}\right)_{estim.}$$

(Eq. 3)

Finally, we calculate the inverse FFT to retrieve the time response. Figure 6-top depicts the time response of both the original 25 µm thermocouple (red dashed line), the original 12.5 µm thermocouple (black dashed line) and the compensated signal (red dotted line). Figure 6 shows that the response of the 25 µm is larger than 8 ms. The compensated 25 µm thermocouple agrees well with the 12.5 µm thermocouple probe.

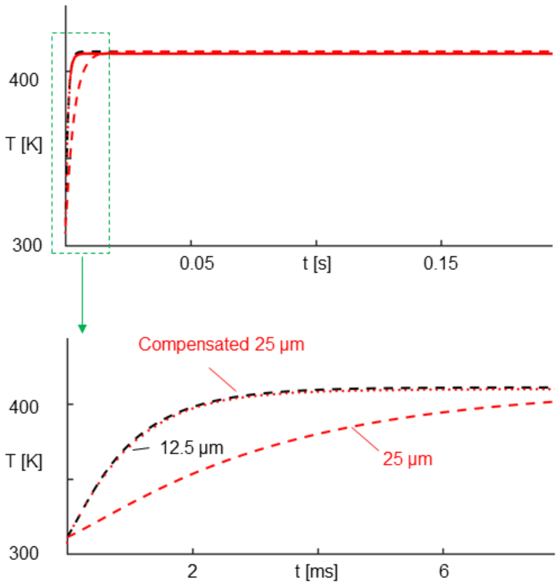

Figure 6: Time evolutions of the 25 µm, 12.5 µm thermocouple and the compensated 25 µm thermocouple.

Figure 7 depicts the relative error between the original time signal and the compensated time signal. The maximum relative error is 1 % and reaches 0.3% at steady state.

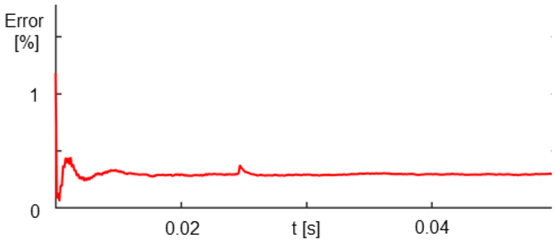

Figure 7: Relative error of the time response between the original 12.5 µm thermocouple and the compensated 25 µm thermocouple.

Alternatively, we could also calculate the compensated time response of the 12.5 µm thermocouple via the 50 µm thermocouple wire. We apply the same procedure as explained for the 25 µm thermocouple wire. The use of the overall recovery factor and the transfer function allow to compensate the 50 µm thermocouple probe into the 12.5 µm thermocouple. Table 3 contains the curve fitting coefficients to compensate the 50 µm into the 12.5 µm thermocouple. The estimated FFT $\left(\frac{\bar{T}_{12.5\ \mu\mathrm{m}}}{\bar{T}_{50\ \mu\mathrm{m}}}\right)_{estim.}$ is recovered and we could finally retrieve an expression for $\bar{T}_{12.5\ \mu\mathrm{m,compensated}}$:

$$\bar{T}_{12.5\ \mu\mathrm{m,comp.}} = \bar{T}_{50\ \mu\mathrm{m}} \cdot \left(\frac{\bar{T}_{12.5\ \mu\mathrm{m}}}{\bar{T}_{50\ \mu\mathrm{m}}}\right)_{estim.}.$$

a	*0.0856 + 0.0891i*
b	*-0.9023 - 0.4708i*
c	*3.0023 + 0.4700i*
d	*0.4766 + 0.6100i*
e	*-1.6635 - 0.7569i*

Table 3: Curve fitting coefficients for the 50 µm thermocouple.

In Figure 8, we depict the compensated time response after applying the inverse Fourier Transform. The blue dashed line represents the original 50 µm from which we obtain the compensated 50 µm signal (blue dotted), in Figure 8—down, we plot a zoom on the step.

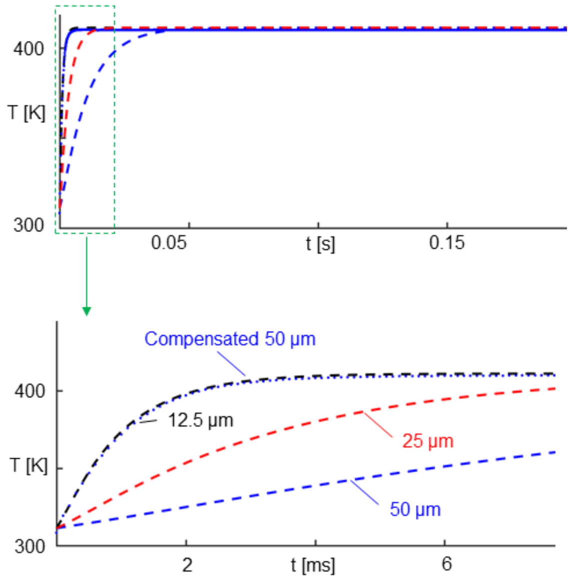

Figure 8: Time evolutions of the 50 µm, 25 µm, 12.5 µm thermocouple and the compensated 50 µm thermocouple.

Figure 9 depicts the relative error of the theoretical signal and the digitally compensated signal from the 50 µm thermocouple, and we observe that the theoretical response to the step was captured within 1 % accuracy and tends to a steady state relative error below 0.3 %, with a similar trend as Figure 7.

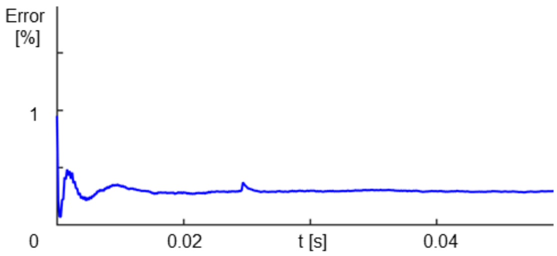

Figure 9: Relative error of the time response between the original 12.5 µm thermocouple and the compensated 50 µm thermocouple

This demonstrates the capability of the dual-junction thermocouple to recover a signal both from the medium thermocouple wire (25 µm) as well as from a large thermocouple wire (50 µm) where the original maximum frequency was bounded to 50 Hz and was enhanced to 150 Hz with this digital compensation.

CONCLUSIONS

In this paper we demonstrated a digital compensation to increase the frequency response of a dual wire thermocouple, with a diameter of 25 µm and 50 µm, to reconstruct a third theoretical thermocouple with a wire diameter of 12.5 µm with a higher frequency resolution.

We first modeled the individual response of each thermocouple and the frequency bandwidth was 15 Hz for the 50 µm diameter thermocouple, 50 Hz for the 25 µm diameter thermocouple and 150 Hz for the theoretical fine wire with 12.5 µm diameter. Afterwards, we evaluated the overall recovery factor which contains the steady state velocity error and conduction error.

Based upon the ratios of the individual FFTs of the dual wire thermocouple signal, we could retrieve a fourth order polynomial fitting that correlates the ratio of the dual-junction thermocouple to the theoretical fine wire thermocouple.

Finally, we applied this method to recover the theoretical step of the fine wire thermocouple. This was performed by using the original signal of the 25 µm wire diameter as well as with the original signal of the 50 µm wire diameter. For both test cases, this resulted into a maximum relative error of 1 % between the digitally compensated signal and the theoretical signal to recover the step. This digital compensation technique offered an increase in frequency response from 50 Hz to 150 Hz.

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