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Research Paper

The lock-in technique applied to heat exchangers: A semi-analytical approach and its application to fouling detection

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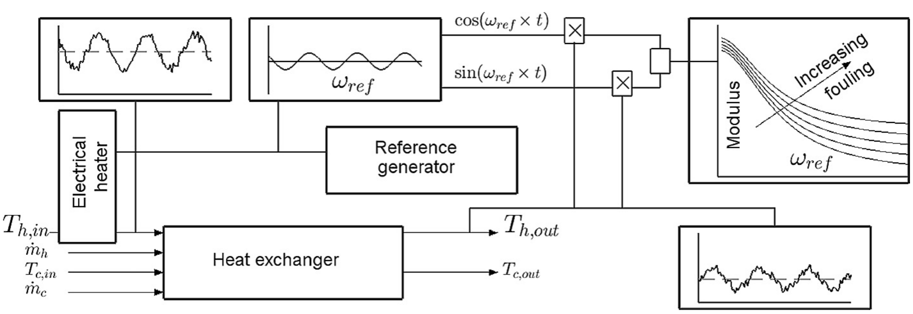
GRAPHICAL ABSTRACT



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ABSTRACT

One of the current methods to detect fouling in heat exchangers is based on the analysis of the evolution of the effectiveness over time. The present results show that, using this kind of analysis, a 6% decrease of the overall heat transfer coefficient cannot be detected when measurement noise (±0.5 °C) is taken into account. On the contrary, the present study shows that the analysis of the evolution of the modulus of the variable computed using the lock-in technique is simple and leads to a very sensitive detection when it is well tuned. In this study, the excitation needed for the application of the lock-in technique is a periodical variation of the inlet temperature of one fluid. It is shown that a 4 million sample sliding observation window is necessary to obtain an accurate value of the modulus. This corresponds to a time span from a few hours up to 5 days, depending on the sampling period. The latter can then be adapted to the expected fouling rate. One important finding is that, in order to detect fouling, the excitation has to be done on the side where fouling is expected.

1. Introduction

The lock-in technique, also called the synchronous detection technique, is a very powerful method for analyzing time series. It is used in various fields such as fluid mechanics [1,2], biomechanics [3], thermography [4]. The main motivation for using this technique is the fact that the synchronous technique provides improved signal-to-noise ratio [5] and high noise rejection characteristics [6]. This is linked to a very high sensitivity [7–9]. It must be noted that these characteristics are balanced by a trade-off between the signal-to-noise ratio and the corresponding measurement time [10]. It is also used for filtering time series [11,12]. It has been shown [13] that the lock-in technique performs better than the Local Narrow-Band Signal decomposition although there is a time lag.

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Nomenclature

A	convective surface area per unit length [m^2/m]
$a_0 = M_h c_h$	heat capacity per unit length of the hot fluid [J/m·K]
$a_1 = \dot{m}_h c_h$	heat capacity rate of the hot fluid [W/K]
$a_2 = h_h A_h$	conductance per unit length of the hot fluid [W/m·K]
$b_0 = M_c c_c$	heat capacity per unit length of the cold fluid [J/m·K]
$b_1 = \dot{m}_c c_c$	heat capacity rate of the cold fluid [W/K]
$b_2 = h_c A_c$	conductance per unit length of the cold fluid [W/m·K]
$c_0 = M_w c_w$	heat capacity per unit length of the separating wall [J/m·K]
c	specific heat [J/kg·K]
D	complex number defined by $D = \frac{(a_2+b_2-c_0 i\ \omega_0)}{(a_2+b_2)^2+(c_0\omega_0)^2}$
E	effectiveness
e	Euler's number
F	complex number defined by $F = a_2 b_2 D = a_F + ib_F$
f_p	reciprocal of the processing time (Fourier series) [s^{-1}]
G	complex number defined by $G = b_2 - b_2^2 D + b_0 i\ \omega_0 = a_G + ib_G$
H	complex number defined by $H = a_2 - a_2^2 D + a_0 i\ \omega_0 = a_H + ib_H$
h	convection coefficient [W/m^2·K]
i	unit imaginary number
j	index
k	index
L	parameter computed by the lock-in technique
M	mass per unit length [kg/m]
$\dot{m}$	mass flow rate [kg/s]
n	number of periods
Re	real part of a complex number
T	period [s], or temperature when used with subscripts [K]
t	time [s]
V	amplitude of the disturbance [K]
x	spatial dimension (abscissa) [m]
Y	amplitude of the component (Fourier series)
y	dummy function
Z	modulus of a complex number

Greek symbols

θ	periodic part of the temperature [K]
ϑ	complex amplitude of the periodic part of the temperature [K]
σ	standard deviation
φ	phase [rad]
ω_0	pulsation [s^{-1}]

Subscripts

$\sim$	periodic
c	cold side
d	disturbance
h	hot side
$\Im$	imaginary part
j	index
k	index
$\Re$	real part
s	steady state
w	separating wall

Superscripts

cos	using the cosine function
in	at the inlet
out	at the outlet
sin	using the sine function

Apart from a specific application where two angular frequencies are used to extract two quantities simultaneously [14], the standard application aims at determining the real and imaginary parts of a complex number [15]. The computation of this complex number is not complicated, as mentioned in [6]. But it must be noted that the excitation angular frequency must be adapted to the phenomenon under supervision [3,7], and must be chosen so that it avoids the "blind frequencies" [16]. This adaptation can be carried out by trial and error, but it is more convenient to use an analytical approach as presented in [17].

Concerning thermal systems, the lock-in technique can be used in the detection of drifts such as fouling. In the increasing complexity order, previous studies have shown the interest of the lock-in technique. Firstly, an analytical approach is presented in [18] for lumped systems; i.e. only time dependent. Secondly, a comparison of theoretical and experimental results is presented in [19] for electrical heaters; i.e. dependent on time and on one spatial function. In the latter, it is shown that there is a zone of interest for the angular frequency used to excite the system. After a first test presented in [21], the present study shows that a simple procedure can be used for heat exchangers (i.e. dependent on time and on two spatial functions) to predict the evolution of what is computed by the lock-in technique versus the angular frequency so that the zone of interest can be easily determined.

2. Principles

Practical use of the lock-in technique consists in exciting the inlet of the studied equipment with a small disturbance at a fixed frequency or reference frequency. In the case of a heat exchanger, this disturbance can be applied either to one of the mass flow rates, or to one of the inlet temperatures of the fluids; the latter is presented in this paper. To cause this disturbance, one easy way is to control the inlet temperature by using an additional electrical heater. Then, the analysis of the outlets of the system (outlet temperatures for a heat exchanger) is carried out using quite simple mathematical tools, i.e. multiplication of the signals by sine and cosine functions having exactly the same frequency as the disturbance. This leads to two time series per outlet as shown hereafter.

Assuming that the behavior of the heat exchanger is linear, the temperature of the fluids and of the separating wall will vary periodically at the frequency of the disturbance. This assumption is valid when the amplitude of the disturbance is sufficiently small. So, consider that the outlet temperature of one fluid is the sum of an arbitrary function that depends on the operating condition and of a fluctuating part having the reference frequency. As the analysis is carried out over a finite duration, the arbitrary function can be represented using a Fourier series. The outlet temperature can then be written as follows:

$$y(t) = \sum_{k=-\infty}^{k=+\infty} Y_k \sin(2\pi k\ f_p t + \varphi_k) + V_\sim^{out} \cos(\omega_0 t + \varphi_\sim)$$

The average value of the product of this function with the periodic function $\cos(\omega_0 t + \varphi_d)$ over a long enough duration is $\frac{1}{2} V_\sim^{out} \cos(\varphi_d - \varphi_\sim)$. The average value of the product with the periodic function $\sin(\omega_0 t + \varphi_d)$ over a long enough duration is $\frac{1}{2} V_\sim^{out} \sin(\varphi_d - \varphi_\sim)$.

Having a phase lag of $\pi/2$, these values can be seen as the real and imaginary parts of a complex number. The latter can be