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Thermal measurements using ultrasonic acoustical pyrometry

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ABSTRACT

Reflections from geometric discontinuities can be used with ultrasonic energy to predict the temperature of an interface where classical temperature measurement techniques are impractical because of physical access limitations or harsh environmental conditions. Additionally, these same ultrasonic measurements can be used with inversion methods commonly applied to ill-posed heat transfer problems to increase the accuracy of the measurement of surface temperature or heat flux at the surface of interest. Both methods for determining surface temperature are presented, along with a comparison of results both from a verification example and using data gathered in a field test of the methods. The results obtained with these two methods are shown to be in good agreement with an empirical relationship used in the design of large caliber guns.

1. Introduction

The vast majority of temperature sensing methodologies require that sensors be placed near, or have access to the location where the thermal measurement is required. Harsh environments, such as those found in combustion chambers, limit the utility of traditional approaches because of the survivability of co-located sensors. Ultrasonic approaches, on the other hand, provide the opportunity to remove the sensor from the deleterious environment, while still querying the thermal response in those environments.

Ultrasonic energy has been used extensively to image living tissue [1], to examine materials for hidden defects [2] and to measure temperature distributions in flue gasses [3]. In general the results of these measurements are not generally concerned with, and usually designed to filter out, high frequency transient events. More importantly, acoustical pyrometry has typically been used to measure average temperatures only and have not been used to extract boundary information such as localized temperatures or heat flux information.

When acoustic energy travels through any material, the transit velocity is temperature dependant. In solid media, the velocity is dependent on thermal expansion and the temperature dependent modulus of the material. Because of the complexity of the relationships, the dependence must be determined experimentally. Knowledge of this temperature dependence and of the dimensions of the domain allows the use of ultrasonic time of flight between surfaces to estimate boundary temperatures. If the reflective surface is exposed to a harsh environment, then this method allows measurement of boundary information not normally available.

Localized boundary temperatures can be approximated when geometry exists that can provide multiple reflections. A reflection from the surface of interest and a distinct reflection from some geometric discontinuity physically adjacent to the boundary of interest provides information about the thermal behavior at an inaccessible location. In this case, the difference between discrete reflections (with different time of flight measurements) from each interface is proportional to the average temperature between the two interfaces. This approach works well when temperature rises are modest and the interfaces are not separated by large distances when compared to the characteristic penetration depth of the material. If the separation between the two surfaces producing reflections is larger than the penetration depth of the domain, the assumption about the differences in wave pulse time of flight being entirely dependent on temperature change begins to break down.

In general, though, this technique is an approximation and more accurate methods are required. Furthermore, it is desirable to be able to estimate boundary temperatures from a single time of flight measurement in order to increase the Nyquist frequency of the measurement system and therefore reveal additional transient behavior. Consequently, inverse techniques have been leveraged to estimate boundary temperatures and heat fluxes using measured ultrasonic time of flight and a forward conduction solution for the domain in which the ultrasonic pulse travels. Unlike traditional inverse heat conduction procedures, the ultrasonic pulse samples the entire domain instead of a single point.

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Nomenclature

E	Young's modulus (Pa)	β	eigenvalue of a differential equation
G	acoustic time of flight (s)	d	diameter (m)
I	area moment of inertia (m^4)	m	mass (kg)
L	domain dimension or length (m)	v	velocity (m/s)
c	acoustic wave propagation speed (m/s)	t	time (s)
T	temperature (K)	ρ	mass density (kg/m^3)
P	linearized change in acoustic velocity (1/K)	z	deflection (m)
θ	temperature change relative to reference (K)	ω	circular frequency (1/s)
k	thermal conductivity (W/m/K)		
q	heat flux (W/m^2)		
α	thermal diffusivity (m^2/s)		

The measurements are still discrete in time leading to amplification of measurement noise. Alternate approaches to the methods presented here, using a finite difference method or an approximation of the domain as infinite, may be seen in the work by Takahashi and Ihara [4,5].

2. Description of the multiple reflection method for determining surface temperature

Consider a one-dimensional isotropic domain that is intended to separate a region of high temperature from a region of lower temperature. A transducer is placed on the external, accessible surface of the domain that is in contact with a region with benign conditions, as shown in Fig. 1.

Note the physical discontinuity on the bounding surface, of width s, on the retaining structure in contact with the harsh environment. This discontinuity is sized such that two distinct reflections from the remote interface are generated and discernable to the data acquisition equipment. A pulse train is generated at the transducer, and two distinct reflection arrivals are recorded as data. Initially the domain is at a constant, known temperature, which is assumed to be the same as the ambient temperature of the external boundary. The time for an acoustical pulse to traverse the domain and reflect back to the transducer is given by:

$$G(T_0) = \frac{2L}{c} \tag{1}$$

where T_0 is the ambient temperature of the domain and the constant temperature of the domain boundary, G is the pulse transit time from the transducer to the far side of the domain and back again via reflection, and L is the dimension of the domain. c is the acoustic velocity of the domain at temperature T_0.

Acoustical velocity, and therefore transit time G, through any medium is a function of temperature. The relationship for G is a function of temperature and can be written

$$G(T) = \frac{G(T_0)}{1 - P(T - T_0)} \tag{2}$$

where P is a constant change in acoustic velocity with change in temperature. Rearranging Eq. (2), yields

$$T = T_0 + \frac{G - G_0}{PG} \tag{3}$$

where G is the time of flight at the current temperature and G_0 is the time of flight with the domain at the initial temperature, T_0. Further defining:

$$\Delta G = G - G_0 \xrightarrow{yields} G = G_0 + \Delta G \tag{4}$$

and making use of a Taylor Series Expansion results in:

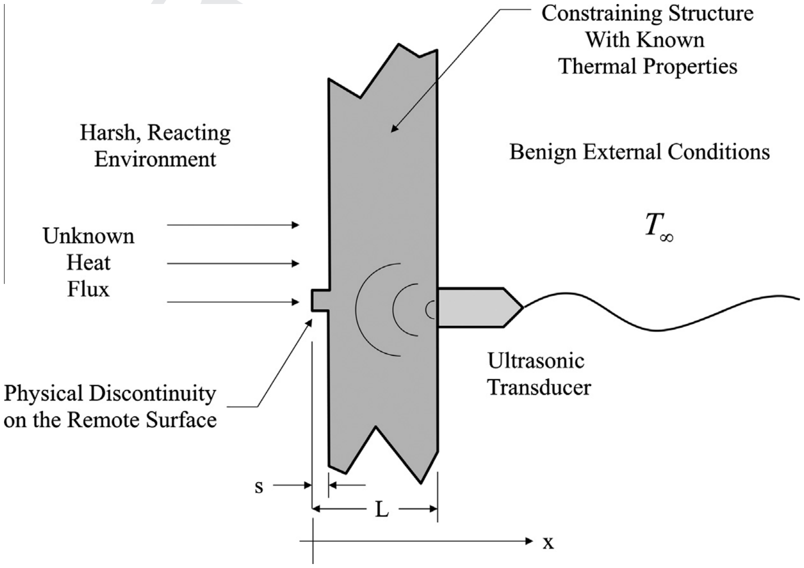

Fig. 1. One dimensional domain, with a geometric discontinuity.

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