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MONITORING AND ANALYSIS OF IN-PILE PHENOMENA IN ADVANCED TEST REACTOR USING ACOUSTIC TELEMETRY

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ABSTRACT

The interior of a nuclear reactor presents a particularly harsh and challenging environment for both sensors and telemetry due to high temperatures and high fluxes of energetic and ionizing particles among the radioactive decay products. A number of research programs are developing acoustic-based sensing approach to take advantage of the acoustic transmission properties of reactor cores. Idaho National Laboratory has installed vibroacoustic receivers on and around the Advanced Test Reactor (ATR) containment vessel to take advantage of acoustically telemetered sensors such as thermoacoustic (TAC) transducers. The installation represents the first step in developing an acoustic telemetry infrastructure. This paper presents the theory of TAC, application of installed vibroacoustic receivers in monitoring the in-pile phenomena inside the ATR, and preliminary data processing results.

Key Words: acoustic telemetry, thermoacoustics sensors, TAC, in-pile monitoring, and data processing.

1 INTRODUCTION

It is believed that listening to a reactor's intrinsic (acoustic emission from normal reactor operation) and extrinsic (active sensor) acoustic sources using the acoustic telemetry infrastructure will allow for an efficient non-intrusive in-pile measurement of temperature, axial extension, fission gases, neutron flux, and gamma flux when coupled with advanced signal processing algorithms, especially under transient testing. Even early detection of failures in structures, pump/vane degradation, and other diverse faults inside reactors is possible with proper sensing and data processing/classification techniques. Multiple signals from several acoustic receivers provide an ability to assess operating conditions with no impact on reactor safety or control systems. The acoustic telemetry research at Idaho National Laboratory (INL) aims to (1) develop acoustic baseline of the Advanced Test Reactor (ATR) under different operating conditions, (2) find quiescent frequency for sensor operating range, (3) develop signal transmission path loss models, and (4) customize denoising techniques to obtain maximum signal-to-noise ratio (SNR) from acoustic sensors.

The theory of acoustic telemetry infrastructure described in this paper will enable researchers to gather information on reactor in-pile phenomena without repeatedly removing samples from a reactor, provide understanding of the experimental sample's end state when each measurement is obtained, enable simulation code validation, refine simulation models, and prevent developing failure. In addition, the outcomes of this research would enable further enhancement of existing acoustic sensor design, such as such as thermoacoustic (TAC) sensors [1], vibroacoustic sensing technology [2], ultrasonic thermometry [3], and development of acoustic communication architecture with high SNR and signal strength.

The paper is organized as follows: Section 2 briefly presents the theoretical background on TAC solution that is used to develop TAC engine. Section 3 describes the acoustic telemetry infrastructure. A laboratory scale set-up of TAC engine and data acquisition module is presented in Section 4 with representative plots. Finally conclusions are drawn in Section 5.

2 A THERMOACOUSTIC SOLUTION

The field of TACs [4], which exploits the interaction between heat and sound waves, offers an attractive solution for development of a self-powered sensor and telemetry system. A device known as a TAC engine produces a high-amplitude sound wave directly from a heat source as the schematic shows in Fig. 1. Heat is applied to the Hot Heat Exchanger end and creates a temperature gradient across the stack. The Cold Heat Exchanger maintains the temperature of the remainder of the engine at ambient or another desired value. As the gas moves to the left (Step 1), heat is transferred from the hot end of the stack to the gas during Step 2, increasing the gas temperature ($T_{++} \rightarrow T_{+++}$) and pressure. In Step 2, since the gas is at a constant high pressure, this increase in gas temperature causes an increase in volume of the parcel of the gas. Consequently, work ($p\Delta V$) is done to the gas by the flow of heat from the stack to the gas. The pressure increase pushes the gas back by a little more each cycle. When the gas moves to the right (Step 3), heat is transferred from the gas to the stack (Step 4), lowering the gas temperature ($T_{+} \rightarrow T_{0}$) and lowering its pressure. Since this removal of heat from the gas occurs at a constant low pressure, the volume of the parcel is decreased and work ($p\Delta V$) is done to the gas. This sucks the gas back toward the hot end of the stack by a little more each cycle. Eventually, the amplitude of the sound wave grows to a steady-state level where the acoustic power dissipated during each cycle is equal to the acoustic power generated by the TAC process. The result is that an acoustic pressure wave is sustained within the engine.

This process of conversion of heat to sound was understood by Lord Rayleigh near the end of the 19th century [4] when he stated that a "vibration is encouraged when heat is added during compression and removed during rarefaction." Gas that sloshes back and forth within the resonator tube has a frequency$f$, and it is related to the length of the resonator L and the sound speed c of the gas within the resonator. In the fundamental half-wavelength configuration, $f = c/2L$ for a closed resonator of uniform cross section. As will be discussed in this article, the speed of sound is related to the temperature of the gas. Such a device can utilize the heat from nuclear fuel and convert this heat into an acoustic oscillation, whose frequency can be correlated to the temperature within the reactor. The sound created by such a "thermoacoustic thermometer" can then propagate through the reactor's coolant and telemeter the temperature data to a remote point without relying on any electrical power.

Fig. 2 provides a schematic representation of how such a sensor would be incorporated into a nuclear fuel rod, which contains a nuclear fuel source toward the right of the schematic. A nuclear fuel rod actually happens to be a closed-closed, half-wavelength acoustic resonator. Heat produced by the fuel reaches the hot end of the stack through electromagnetic radiation (EMR), and acoustically driven streaming gas flow, indicated by the oval arrows, moves heat to the other end of the stack by convection, depositing heat on the walls of the fuel rod, which are surrounded by coolant fluid. This maintains an adequate temperature gradient across the stack to produce a high-amplitude acoustic standing wave without the hot and cold heat exchangers that are used in more traditional standing-wave TAC engines [5-7].

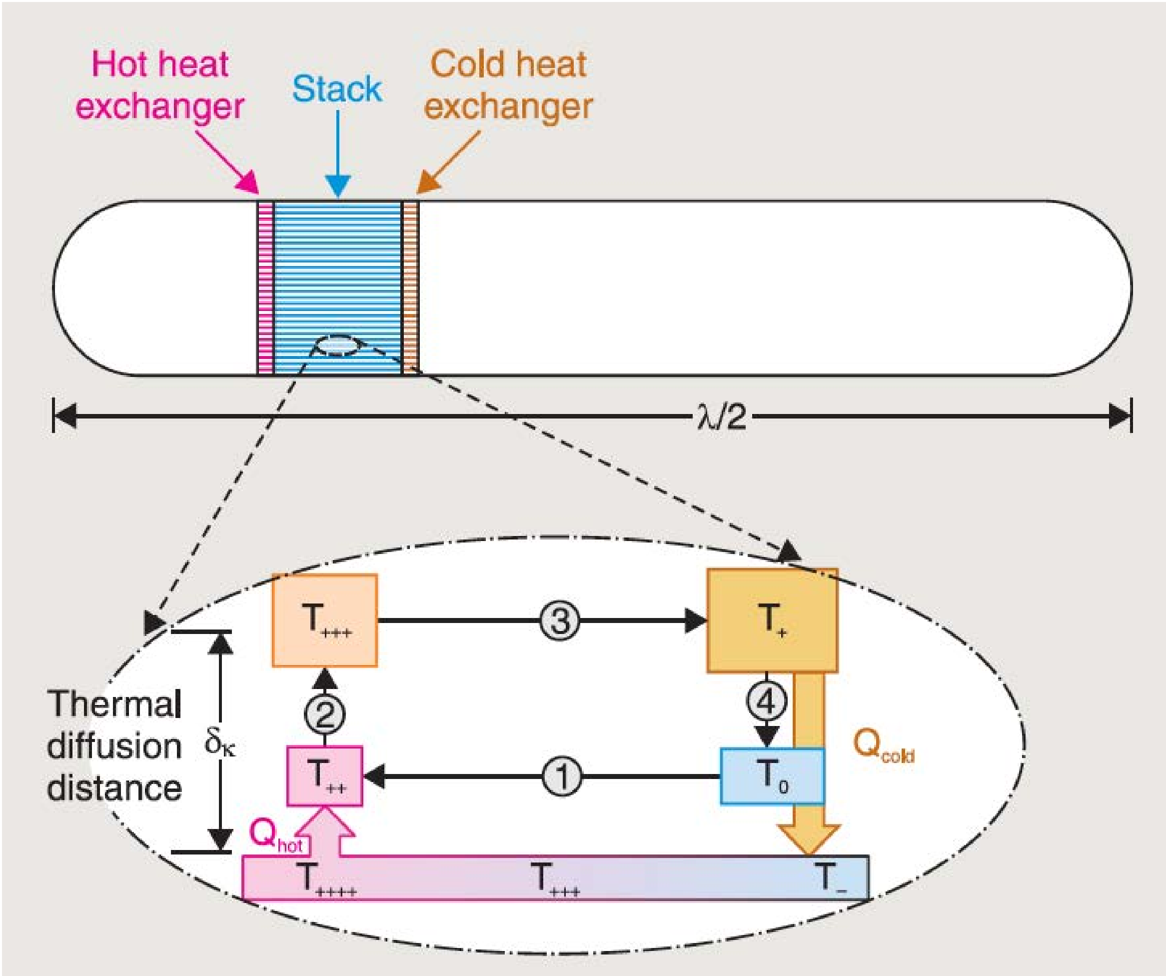


Figure 1. A schematic view of the operation of a half wavelength long thermoacoustic engine [4–6].

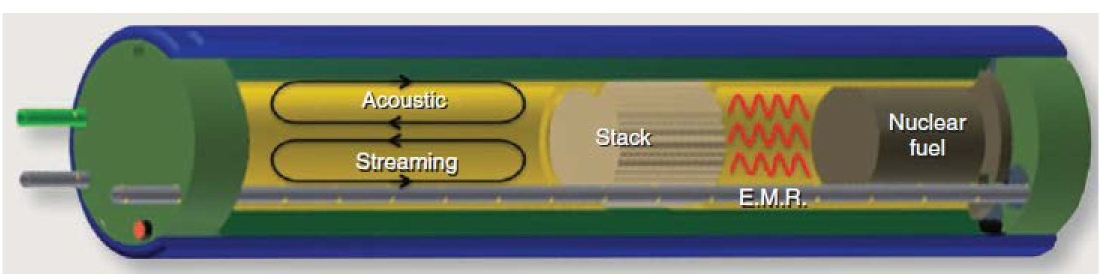


Figure 2. Schematic representation of a nuclear fuel rod that contains a "stack" to produce thermoacoustic engine [5–6].

3 ACOUSTIC TELEMETRY INFRASTRUCTURE

The TAC solution described in Section 2 presents an opportunity to develop the acoustic telemetry infrastructure, as shown in Fig. 3 for in-pile ATR and Transient Test Reactor monitoring (TREAT). It is a novel approach that relies on data being transmitted wirelessly from inside to outside of the reactor. The

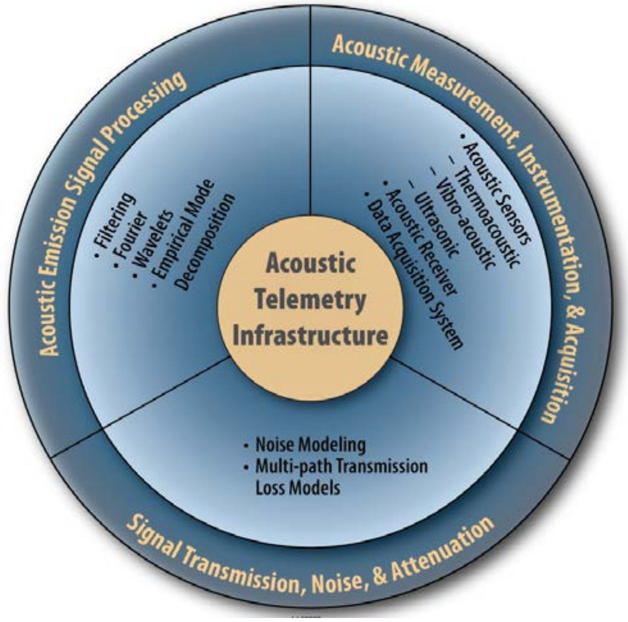


Figure 3. Elements of proposed acoustic telemetry infrastructure for in-pile phenomena characterization.

approach is practical as it provides INL, ATR National Scientific User Facility, and TREAT, with the unique ability to perform non-intrusive in-reactor measurements of materials during irradiation. The wireless transmission discussed refers to the transmission of sound via fluids, mechanical structures, pipes, and conduits. The transmission of signal will allow users and experimenters to access raw data, process the data using the acoustic emission signal processing element (Fig. 3), and extract information from the signal while the experiment is still in process inside the reactor [8].

3.1 Acoustic Measurement, Instrumentation, and Acquisition

In total, eight vibroacoustic receivers are installed on the exterior of the advanced test reactor pressure vessel and on supporting structures within the nozzle trench access area to monitor acoustic signals emanating from within the core. The acoustic data will be recorded and transferred to a remote center where it will be stored and processed.

3.2 Signal Transmission, Noise, and Attenuation

In complex environment such as nuclear reactor, multiple noise sources are observed. The frequency and intensity of individual noise source and possible interaction between them could conceal the concern underlying actual signal of interest and significantly affects the SNR of the measured signal. Another concern associated with transmission of acoustic signal via fluid, metal pipes, and other reactor structures is attenuation (i.e., decrease in signal strength).

Fractional Gaussian noise is a generalization of white noise [9] and will be studied in the proposed research. It is closely linked with self-similar stochastic processes and random fractals, both of which have been extensively considered in signal processing applications. It is expressed as incremental process of fractional Brownian motion and its statistical properties are controlled by a single parameter H known as the Hurst exponent. For detailed discussion on statistical properties of the noise model, refer to Mandelbrot and Ness's 1968 article [9]. The value H is within the range $[0,1]$ and $H = 0.5$ corresponds to white Gaussian noise.

In nuclear infrastructure, the environment is very different; the assumption of free space is not realistic. The signal traverses through different mediums (vessel wall, piping, fluids, concrete structures, etc.) with different attenuation factors (depending on the mass of the medium) before reaching the user-located receiver. In addition, the acoustic receivers will be located at different locations (i.e., access points) to record the signal. The path loss observed at each access point will be different because vessel wall, piping, conduits, and concrete structure have different attenuation factor. In this case, a multipath propagation model is required. A detailed formulation of path loss model for different sensor configuration will be developed.

These noise model(s) will be updated based on extracted intrinsic mode functions corresponding to the ATR noise under different operating conditions.

3.3 Acoustic Emission Signal Processing

The acoustic emission signal processing element of the proposed research will develop signal processing techniques that will enable investigators to denoise and detrend acoustic signals with different SNR and signal strength so that ATR operational acoustic baseline can be established for given operational conditions. The SNR and signal strength ranges will be based on the noise model(s) and path loss models, respectively.

The AESP element of the proposed research will focus on (1) denoising and (2) detrending acoustic signal. In this proposed research, investigators will utlitize an empirical multiresolution decomposition technique to process time-frequency analysis of measured multivariate signals. The methodology known as empirical mode decomposition (EMD) [10] will be used to pre-process measured signals. The EMD technique does not use any pre-defined filter or Wavelet function and is a fully data-driven method. Since the decomposition of the EMD is based on the local characteristics time scale of the data, it is applicable to nonlinear and non-stationary processes.

EMD decomposes the measured signal into number of instrinsic mode functions (IMFs) based on two general assumptions: (1) each intrinsic mode must have the same number of extrema and zero crossings or differ at most by one and (2) must be symmetric with respect to the local zero mean. These two assumptions assist in defining a meaningful instantaneous frequency of an IMF. Based on these assumptions, the sifting procedure to obtain IMFs of the signal $x(t)$ is described as follows:

1. Identify all the maxima and the minima in the signal $x(t)$.
2. Generate its upper and lower envelopes using cubic spline interpolation.
3. Compute the point-by-point local mean m_1 from upper and lower envelopes.
4. Extract the details $h_1 = x(t) - m_1$.
5. Check the properties of h_1 and iterate k times, then $h_{1k} = h_{1(k-1)} - m_{1k}$ becomes the IMF once it satisfies some stopping criterion. It is designated as first IMF $c_1 = h_{1k}$.
6. Repeat Steps 1 through 5 on the extracted data $r_1 = x(t) - c_1$.
7. Repeat Step 6 until all the IMFs and residual are obtained.

The stopping criterion, the normalized squared difference between two successive sifting operations is defined as:

$$\mathrm{SD_k} = \frac{\sum_{t=1}^{T} |h_{k-1}(t) - h_k(t)|^2}{\sum_{t=1}^{T} h_{k-1}^2} \quad (1)$$

The SD_k value is generally set between 0.2 and 0.3. In the detrending process, the decomposed signal can be represented as:

$$x(t) = \sum_{j=1}^{N} \mathrm{IMF_j}(t) + r_N(t) \quad (2)$$

where $j = \{1, \ldots, N\}$, N is the total number of IMFs and $r_N(t)$ is the final residue, which can be either the mean trend or a constant. The name IMF is adapted because it represents the oscillatory mode embedded in the measured signal. With this definition, the IMF involves only one mode of oscillation, no complex riding waves are allowed.

Given the decomposed signal information in terms of IMFs, the denoising principle proposed here is described as follows. Let $f_j(t)$ be a noiseless IMF and $IMF_j(t)$ its noisy version. If the measured signal $x(t)$ is corrupted by additive noise $b_j(t)$ with a noise level $g_j(t)$, then:

$$\mathrm{IMF_j(t) = f_j(t) + g_j(t)} \tag{3}$$

An estimation $\widetilde{f_j}(t)$ of $f_j(t)$ based on the noisy observation $IMF_j(t)$ is given by:

$$\mathrm{\widetilde{f_j}(t) = \Gamma\left[IMF_j(t), \tau_j\right]} \tag{4}$$

where $\Gamma\left[IMF_j(t), \tau_j\right]$ is a preprocessing function, defined by a set of parameters τ_j, applied to signal $IMF_j(t)$. The denoising signal $\widetilde{x_j}(t)$ is given by:

$$\mathrm{\tilde{x}(t) = \sum_{j=1}^{N} \widetilde{f_j}(t) + r_N(t)} \tag{5}$$

In addition to EMD, different kinds of preprocessing function will be evaluated such as temporal filtering, nonlinear transformation, statistical characterization, and so on. In addition, the proposal will also implement classical techniques based on filtering, Fourier transformation, and wavelets.

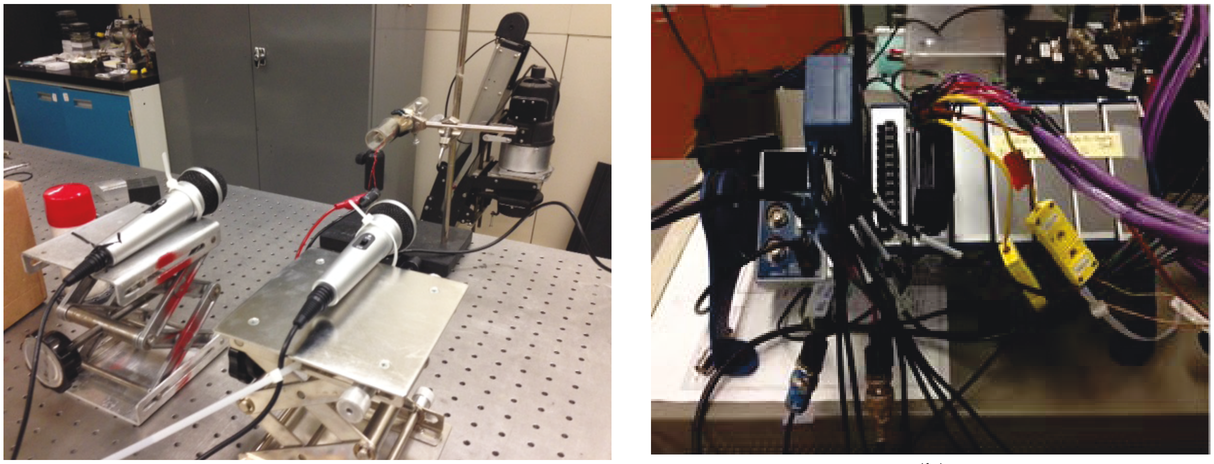
4 LABORATORY EXPERIMENTAL STEP-UP

An experimental setup at INL is described that generate TAC data as per the TAC engine described in Section 2. Here the stack, made of porous insulating material, maintains a temperature gradient across its length. Heated air on the hot side of the stack is forced through the resonator tube where it quickly cools and is pulled back along the temperature gradient. In this way, a resonance is established with the glass cylinder, resulting in a fixed frequency, audible signal.

A set of two microphones (shown in Fig. 4[a]) is used to collect the audible tone. The microphones are easily positioned at various relative distances from the tone source, allowing for a study of phase relationships between the two detected signals. The low-voltage microphone signals are digitized using a commercially available, modular National Instruments (see Fig. 4[b]) analog to digital converter. An INL-developed data acquisition system controls the sampling rates and configuration for the data acquisition, and provides real time display of both the raw data, as well as the Fourier transform displays of frequency and amplitude of the TAC signal.

The amplitude of the TAC signal is proportional to the source energy, which might be the neutron flux. The frequency is a function of the length of the TAC sensor and the fluid contained within the resonator. The speed of sound within the fluid changes with temperature and thus frequency changes. The representative amplitude and frequency plots of Microphone 1 are shown in Fig. 5 and Fig. 6, respectively. A similar amplitude and frequency plots are obtained for Microphone 2.

In Fig. 6, the change in the frequency is due to increase of the stack temperature. As the heating element heats up, the fluid inside the resonator warms up. As the device approaches steady state, the frequency approaches a constant value.



(a) (b)

Figure 4. TAC air resonator and two detector microphones (a) and A/D convertor module (b).

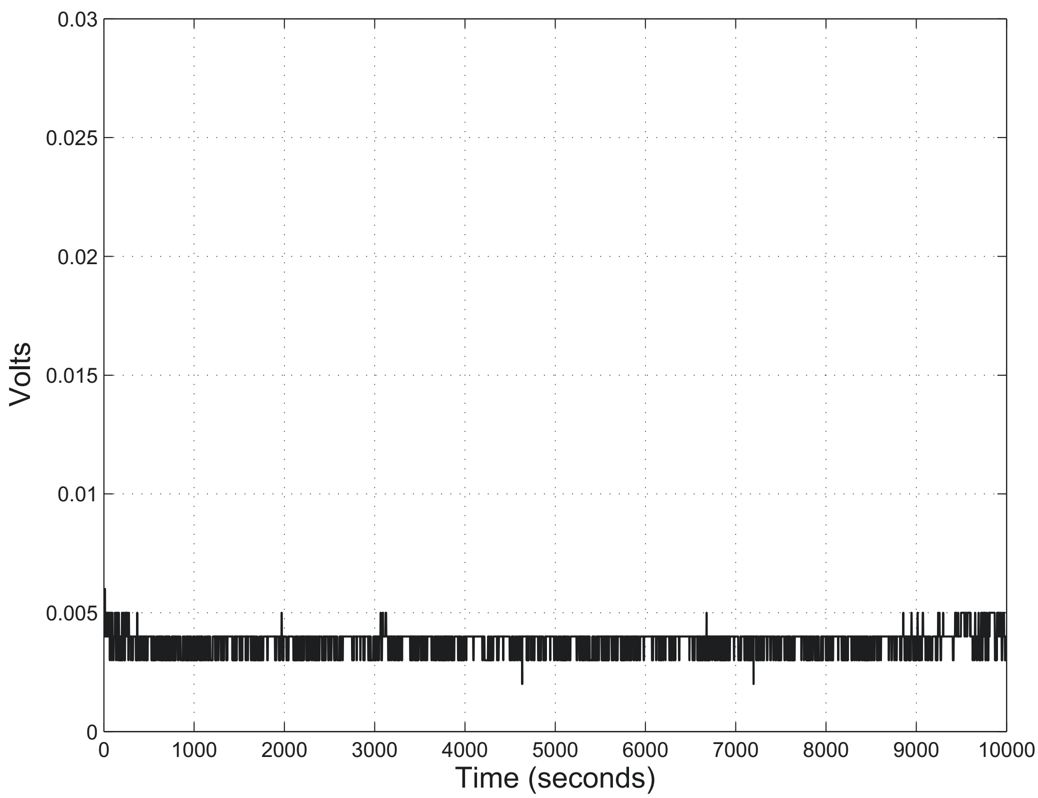


Figure 5. Amplitude of the TAC signal measured using Microphone 1.

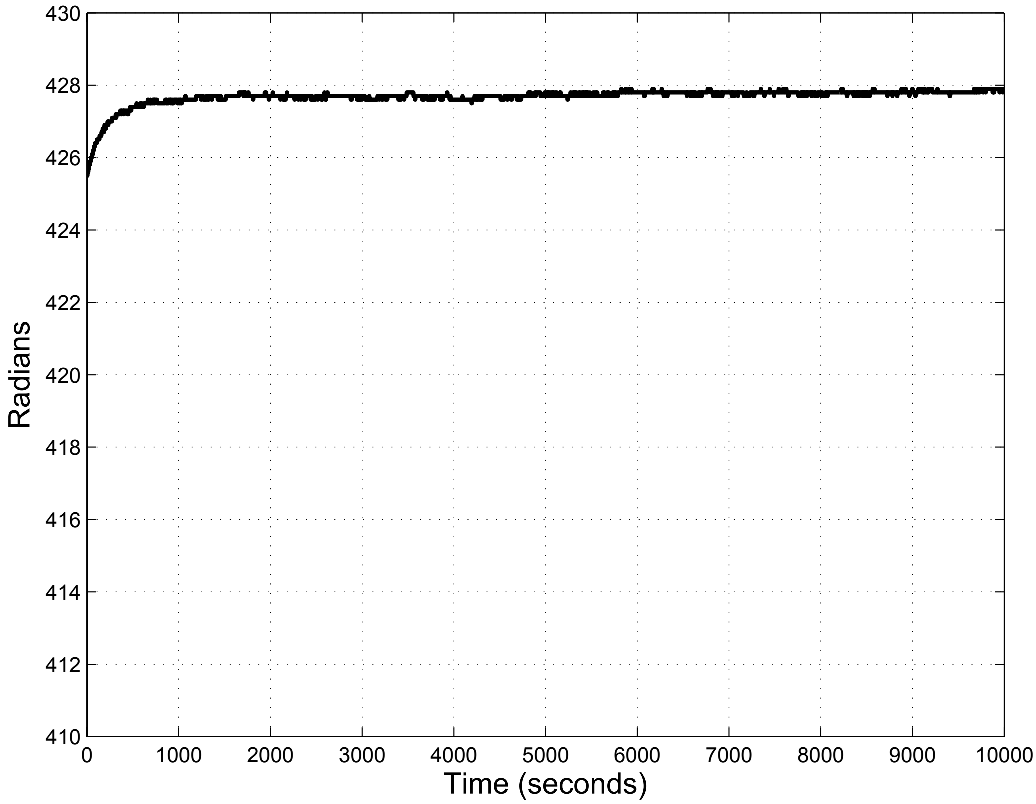


Figure 6. Frequency of the TAC signal measured using Microphone 1.

5 CONCLUSIONS

The theory of TAC sensing solution is presented in this paper highlighting an opportunity for researchers to develop an acoustic telemetry infrastructure to perform reactor in-pile measurements. This is demonstrated via a laboratory step-up of TAC and representative signals obtained. The representative amplitude and frequency collected using the laboratory set-up was presented. The signal processing algorithm, EMD, described is data-driven that will be utilized to denoising and detrending acoustic signals. As part of the future research, the proposed approach will be used to establish acoustic baseline of ATR under different operating modes based on the installed sensors.

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