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PREDICTIVE MODELING OF ACOUSTIC SIGNALS FROM THERMOACOUSTIC POWER SENSORS (TAPS)

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ABSTRACT

Thermoacoustic Power Sensor (TAPS) technology offers the potential for self-powered, wireless measurement of nuclear reactor core operating conditions. TAPS are based on thermoacoustic engines, which harness thermal energy from fission reactions to generate acoustic waves by virtue of gas motion through a porous stack of thermally nonconductive material. TAPS can be placed in the core, where they generate acoustic waves whose frequency and amplitude are proportional to the local temperature and radiation flux, respectively. TAPS acoustic signals are not measured directly at the TAPS; rather, they propagate wirelessly from an individual TAPS through the reactor, and ultimately to a low-power receiver network on the vessel's exterior. In order to rely on TAPS as primary instrumentation, reactor-specific models which account for geometric/acoustic complexities in the signal propagation environment must be used to predict the amplitude and frequency of TAPS signals at receiver locations. The reactor state may then be derived by comparing receiver signals to the reference levels established by predictive modeling. In this paper, we develop and experimentally benchmark a methodology for predictive modeling of the signals generated by a TAPS system, with the intent of subsequently extending these efforts to modeling of TAPS in a liquid sodium environment.

Keywords: thermoacoustics, wireless in-core radiation detection, wireless in-core temperature sensing, vibro-acoustic measurement

This paper is organized as follows:

- Section 1 provides an introduction to the project
- Section 2 describes the benefits of TAPS technology
- Section 3 provides an introduction on the theory behind thermoacoustic engines
- Section 4 describes the TAPS used in the experiment and the role of its internal components in the thermoacoustic mechanisms
- Section 5 describes the analytical lumped-parameter model used for predicting the amount of useful thermoacoustic heat in the TAPS
- Section 6 describes the DeltaEC software and model used to predict the performance of the thermoacoustic engine
- Section 7 describes the finite element structural-acoustic model used to predict the amplitude of TAPS signals measured by the TAPS receiver network
- Section 8 describes the experimental activities
- Section 9 presents the results of the comparison between experimental observations and modeling
- Section 10 outlines conclusions and future work

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1. INTRODUCTION

Thermoacoustic Power Sensor (TAPS) technology offers the potential for self-powered, wireless measurement of the operating conditions in a nuclear reactor core. A TAPS is a ~200 mm long cylindrical sensor, axially spring-mounted on a frame, which converts harvested radiation flux into acoustic waves (sound waves). TAPS can be positioned in fuel assemblies (for example, in the instrumentation tube), although exact placement details can vary depending on fuel assembly geometry considerations. The frequency of the sound waves generated by a TAPS can be related to the local coolant temperature, while the wave amplitude is proportional to the local radiation flux. These sound waves propagate through the reactor core until they reach the reactor vessel, where fluid-structural coupling results in vibration of the reactor vessel walls. A set of receivers mounted on the reactor vessel's exterior can then measure the transmitted vibrations. After signal processing and corrections, a wirelessly-transmitted, real-time measurement of the temperature and radiation conditions in the core is obtained.

Interpretation of the signals measured by the network of external receivers poses its own set of challenges which must be addressed before TAPS can be relied on as a measurement instrument. If an accelerometer could be mounted directly on a TAPS, determining the frequency and amplitude of the TAPS vibrations (and thus, the temperature and radiation flux in the core) would be straightforward. However, accelerometers and related cabling cannot withstand the harsh environment in a nuclear reactor core, which, combined with the need to minimize cable penetrations through the reactor vessel walls, render such a measurement system unviable. As a consequence, since the acoustic signals travel through the reactor core and the TAPS vibrations are observed at a remote location, the measurement process becomes more complex and requires corrections to be made in signal processing. The closed reactor vessel will resonate at its structural modes and the coolant volume will resonate at its acoustic modes – both of which are coupled, and will be apparent in the measured vibration signals. The fuel assemblies and other internal structures in the reactor will introduce reflection and absorption of sound waves. Thermal gradients in the reactor can also affect the propagation of sound. Finally, coolant flow and pumps will introduce mechanically- and flow-induced noise, as well as convective effects, that will interfere with the TAPS signals.

Current TAPS development is focused on developing a modeling methodology that can predict the amplitude and frequency of TAPS signals at receiver locations. The reactor state (local temperature and neutron flux) can then be obtained by examining the proportionality of the receiver data and the "reference levels" anticipated by predictive modeling. At present, development of the modeling methodology is focused on addressing a subset of the signal interpretation challenges just listed: predicting the amplitude of TAPS vibration by applying thermoacoustic theory to known TAPS hardware; and using finite-element simulation to predict the characteristics of the vibrations measured by an external receiver network in a static fluid. At a schematic level, the modeling methods discussed herein involve first predicting the amplitude and frequency of the TAPS with a thermoacoustic simulation in DeltaEC, a thermoacoustic analysis package developed by researchers at Los Alamos National Laboratory [1]. The TAPS body vibrations predicted by the DeltaEC model are then used as input conditions in a coupled structural-acoustic finite-element model of the vessel under consideration, implemented in ANSYS® Mechanical™ (hereafter, for brevity, referred to as "ANSYS"). The results of this set of simulations include the vibration anticipated on the outside wall of the vessel. These predictions of TAPS signals will be used as the "reference level" for comparison to the direct measurements made by accelerometers in the receiver network. Experiments using electrically-powered hardware were performed to validate the modeling methodology, which was found to be an accurate predictor of the TAPS signals as measured on the exterior of a vessel.

2. BENEFITS OF TAPS TECHNOLOGY

In order to identify where and how TAPS might be a helpful addition to the general body of core monitoring technology, a short survey of common measurement instruments is in order. Typical water-cooled nuclear reactors rely on a series of radiation monitors and specialized thermocouples in order to obtain real-time feedback on the radiation flux and temperature conditions within a reactor core. These instruments must be sealed and capable of withstanding high temperatures, radiation, and long periods between servicing in order to be viable, which are all significant design-phase challenges. In addition, each of these instruments requires a penetration through the reactor vessel for electrical connections; each additional penetration adds manufacturing complexity and represents a potential path for a loss-of-coolant event. As a result, the number of sensors is currently limited, producing relatively coarse core power measurements.

Since TAPS are powered via a small amount of radiation flux and the output signal is a physical vibration, the sensors are completely wireless, thereby eliminating several of these instrument and vessel design challenges. A TAPS can be placed into a reactor (including existing reactors), for example as 3-4 TAPS axially distributed within fuel assembly instrumentation tubes, and a network of receivers, such as accelerometers, can be mounted on the exterior of the reactor vessel to measure the sensor output. An array of TAPS deployed throughout the reactor core would provide a real-time, three-dimensional map of average temperature and radiation flux. During normal operation, such information would allow recapture of temperature and heat flux margins, enabling reactor power to be increased (without reducing safety margins) and additional revenue to be generated. However, the wireless nature of these sensors would also eliminate inspection and maintenance of instrumentation wiring during outages, shorten outage duration, and as a consequence, potentially save millions of dollars in operations and maintenance costs.

TAPS technology is particularly advantageous when considering its use in liquid metal-cooled reactors. Sodium-cooled fast reactors (SFRs) must be provided with core

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instrumentation capable of handling the much higher fast neutron and gamma flux, and temperature, relative to water-cooled reactors, as well as compatibility with liquid metal coolants. In part due to these challenges, very little instrumentation is placed inside SFR cores, and radiation monitors (in the form of fission chambers) are generally located below the core, where radiation flux and temperatures are lower. TAPS technology may eliminate this practical limitation: TAPS are purely “physical systems,” and therefore contain no electronics or materials that can easily deteriorate under the harsh operating conditions characterizing SFR cores. Therefore, appropriately-configured TAPS could be used within the core of a liquid metal reactor such as a SFR: they can tolerate direct exposure to the mentioned conditions without experiencing unacceptable performance degradation or requiring excessive maintenance in the long-term.

A final, and perhaps most important, advantage of a TAPS monitoring system is improved plant safety. While improved core measurement accuracy is always welcome, the spatial measurements generated by a TAPS array would be extremely useful in anomaly detection, such as a local blockage in coolant flow – quite literally, the increased temperatures resulting from reduced cooling would make the TAPS cylinders “scream” at higher pitches, thus indicating the presence of such an anomaly. Moreover, in the event of a station blackout, a TAPS system would continuously provide critical information regarding the reactor state. The radiation flux-powered TAPS would continue generating sound waves even in the absence of station power and, unlike conventional instrumentation which requires a non-negligible amount of power to operate, the low-power receiver network could be energized with either batteries or via a passive mechanism such as gamma energy harvesting. The core state measurements generated by TAPS arrays would be an extremely useful aid in the decision-making process during any anomalous event.

3. INTRODUCTION TO THERMOACOUSTICS

The core physical process underlying TAPS technology is thermoacoustics: the interaction of heat and acoustic (sound) waves. Thermoacoustically-generated sound waves can be observed when a hot glass bulb is connected to a cold tube. When investigating this phenomenon, Lord Rayleigh described a mechanism: “If heat be given to the air at the moment of greatest condensation, or taken from it at the moment of greatest rarefaction, the vibration is encouraged.” [2] TAPS technology harnesses this same thermoacoustic phenomenon: it serves as a mechanism to convert thermal energy to acoustic energy. In that sense, it is completely accurate to refer to a TAPS as a heat engine with a thermoacoustic cycle: an input of heat is converted to work. However, the output work is acoustic work, rather than the typical rotary work which results from the use of automobile engines and power generation turbines. Like any engine, a TAPS will respond to greater power inputs with greater work output: as more heat is introduced to the sensor, larger-scale molecular motion will occur between the heating and cooling portions of the engine cycle, resulting in greater local gas pressure and velocity fluctuations.

A schematic of the internal configuration of a TAPS is shown in Fig. 1. The TAPS, immersed in the core of a reactor, generates sound by the motion of internal fluid due to heat transfer. In the “hot end” of the tube, heat is transferred to the working thermoacoustic fluid, a gas, by some heat source. In the case of the experiments described here, the heat source (and heat exchanger) is an electrical heater made of nichrome wire. In an actual nuclear application, the heat source could be a fuel pellet or a piece of gamma ray-absorber material. Upon receiving heat, the local gas pressure increases, resulting in motion of air molecules away from the high-temperature area. These heated molecules move towards the cold end of the TAPS, which is cooled by the reactor coolant, through the heat exchanger and the “stack” – a piece of material that serves to maintain a temperature gradient across the TAPS body, and also the site where thermoacoustic oscillations occur. As the hot gas

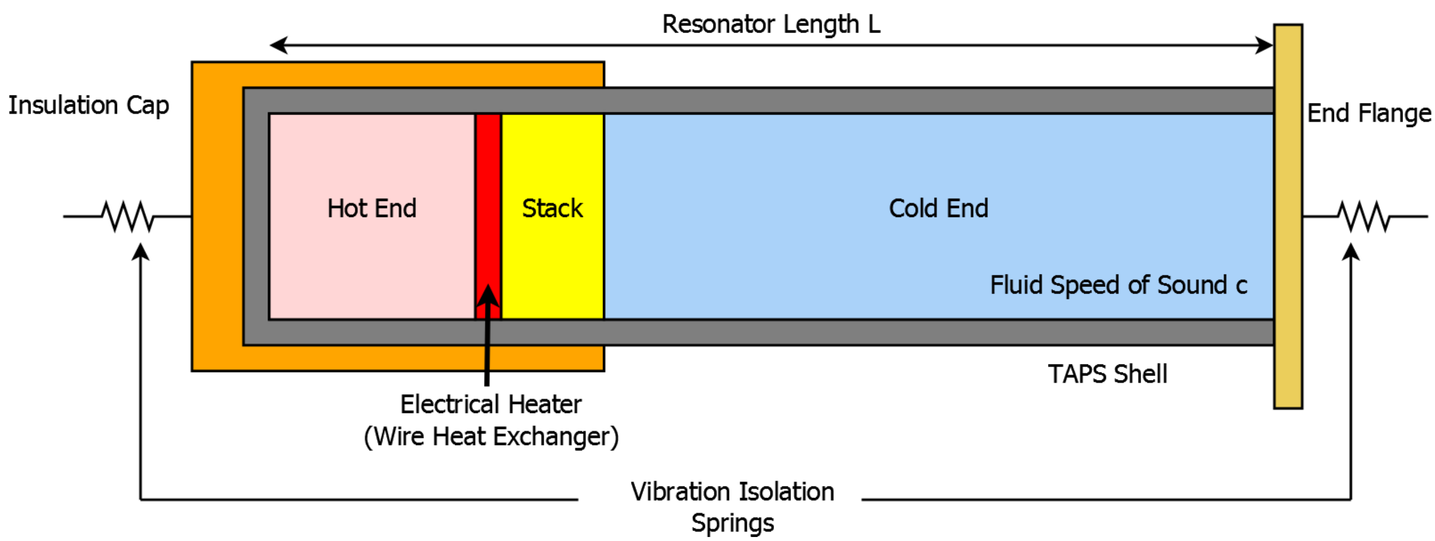

FIGURE 1: SCHEMATIC CUTAWAY VIEW OF A TAPS

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molecules move away from the site of heating and toward this cooler temperature (and lower pressure), they collide with other gas molecules, and transfer energy in the manner stipulated by the kinetic-molecular theory of gases. Upon losing the thermal energy absorbed from the heat exchanger, the local gas pressure decreases. Low pressure results in molecular motion towards the heat source, where the molecules absorb additional heat, and the cycle repeats.

The vibration of gas molecules near the heat source and inside the thermoacoustic stack propagate down the TAPS body, which is essentially a column of fluid. Thermoacoustic oscillations add energy to an acoustic system, and the sound ultimately heard by an observer will be the result of this energy causing the system to "ring out" at its acoustic natural frequencies – in the case of the TAPS, the solution to the acoustic wave equation with reflecting boundary conditions. A tube with closed-closed ends has a specific name in the acoustics field: a half-wave resonator. Equation 1 can be used as a first-pass approximation to calculate the frequency of such a resonator in Hertz, where L is the tube length and c is the speed of sound in the fluid filling the resonator.

$$f = \frac{c}{2L} \tag{1}$$

4. TAPS CONSTRUCTION AND MECHANISMS

A TAPS appropriate for use inside a nuclear reactor must be a hermetically-sealed device. Thermoacoustic resonance must take place inside the body of the TAPS cylinder, and these vibrations must be transferred from the cylinder to the outside environment in order to transmit wireless measurement data. A method for constructing a sealed standing-wave thermoacoustic resonator was developed in a synergistic project by S. Garrett, et al. [3]. An electrically-heated prototype from that project, shown in Fig. 2, was used in the experimental portion of the present investigation. Further details in this section will provide information on TAPS components – focus will be placed on the elements which are relevant to predictive signal modeling.

4.1 Hot Reservoir

In order to build a working thermoacoustic power sensor, a "hot reservoir" or "hot end" is needed – a region which maintains a constant temperature for a steady power input. As mentioned previously, a TAPS is powered by harvested radiation flux – flux passes through the hermetically-sealed shell (in this TAPS, made of stainless steel) and can reach a radiation absorber inside the TAPS [4]. Inside the resonator tube, there is a designated hot reservoir – in Figs. 1 and 2, the end of the TAPS with the large-diameter cylinder. In a TAPS intended for use in a reactor, the "hot reservoir" contains material which can convert radiation flux to a useful heat source. As mentioned previously, two examples of possible TAPS heat sources are fuel pellets and gamma absorbers. These heat sources must be isolated from the reactor coolant – with direct coolant exposure and only the TAPS shell as insulation, heat would be transferred to the coolant in the same manner as standard fuel assemblies, leaving an insufficient amount of heat to operate the thermoacoustic engine. For this reason, the aforementioned large-diameter cylinder on the hot end of the TAPS is insulated to reduce heat leaks to acceptable levels. As the radiation flux changes, the amount of useful heat available for thermoacoustics can be described as a function of various possible non-thermoacoustic paths for heat to travel. The main heat leak paths are losses through the insulation and through the shell of the TAPS. A thermal model incorporating the exact construction of the "hot end" can predict the amount of heat that is available to drive thermoacoustic sound generation. Thus, this thermal model can be used to accurately estimate the measured sound wave amplitude for a given local radiation flux level. Discussion of this model may be found in the "Lumped-Parameter Thermal Model" section. Note that in the experiments described in this paper, an electrical resistance heater was used to provide known quantities of input power.

4.2 Cold Reservoir

A cold reservoir is also necessary in order to initiate thermoacoustic vibrations; as with any heat engine, waste heat

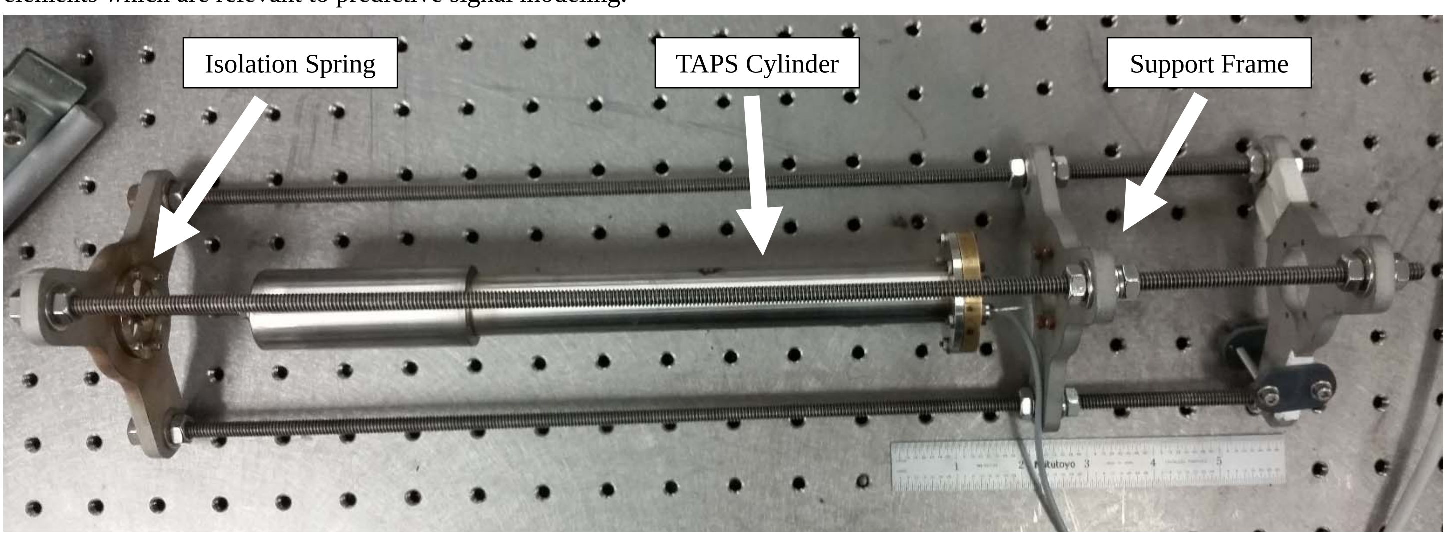

FIGURE 2: EXPERIMENTAL TAPS MOUNTED IN FRAME

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must be rejected when converting thermal energy into work. In a reactor, the environment must absorb the heat rejected by the engine. The thinnest portion of the TAPS in Figs. 1 and 2 contains only thermoacoustic working fluid, which is cooled through the resonator walls by convection with the reactor coolant. Thus, the working fluid in this “cold end" of the resonator acts as a prototypical heat sink at the temperature of the reactor coolant. Previously, the assertion was made that the TAPS output frequency was proportional to the coolant temperature. This assertion is explored more thoroughly in [5]. Recalling Eq. 1, the frequency of an acoustic resonator is proportional to the speed of sound of the resonator; thus, as the temperature of a gas rises and the speed of sound increases, the frequency of thermoacoustic vibrations increases; by this mechanism, a TAPS gains its thermometry capabilities.

4.3 Thermoacoustic Stack

A standing temperature gradient alone is insufficient to create thermoacoustic vibrations. A “stack”, shown in Fig. 3, was previously mentioned as the location where thermoacoustic oscillations occur. A stack is a piece of material containing thin channels through which the thermoacoustic fluid may move. A side view of the stack is shown at the bottom of Fig. 4. The stack serves two functions: first, it maintains the temperature gradient between the hot and cold ends; and second, its small channels and great surface area assist in the transfer of heat between the fluid and the surface of the stack, which absorbs heat from the heat exchanger/hot reservoir and is the point of initiation for thermoacoustic oscillations. The stack surface and nearby fluid is brought to localized high and low temperatures by the hot and cold reservoirs (heat exchangers). Fluid in the stack channels is sufficiently isolated from the environment to excite the back-

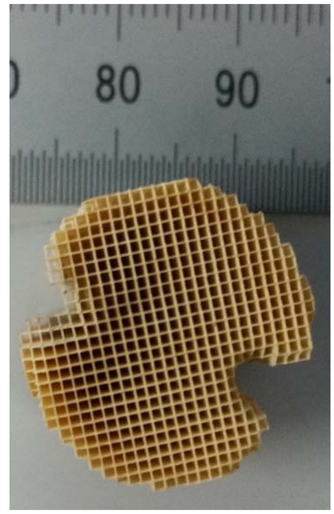

FIGURE 3: TOP VIEW OF CERAMIC STACK, WITH SCALE.

and-forth vibrational motion and heat transfer described previously. Since a good thermoacoustic stack does not have perfectly-coupled heat transfer with the working fluid, a delay exists in the expansion/compression cycle relative to the motion of fluid, resulting in irreversible work generation. (In contrast, an in-phase relationship between thermoacoustic working fluid pressure and velocity would result in a reversible process, and no work generation.)

4.4 Wave Propagation from a Sealed Resonator

The acoustic waves from a TAPS must be transferred to the environment by a physical mechanism. In an open-air thermoacoustic device which uses air as a working fluid, audible

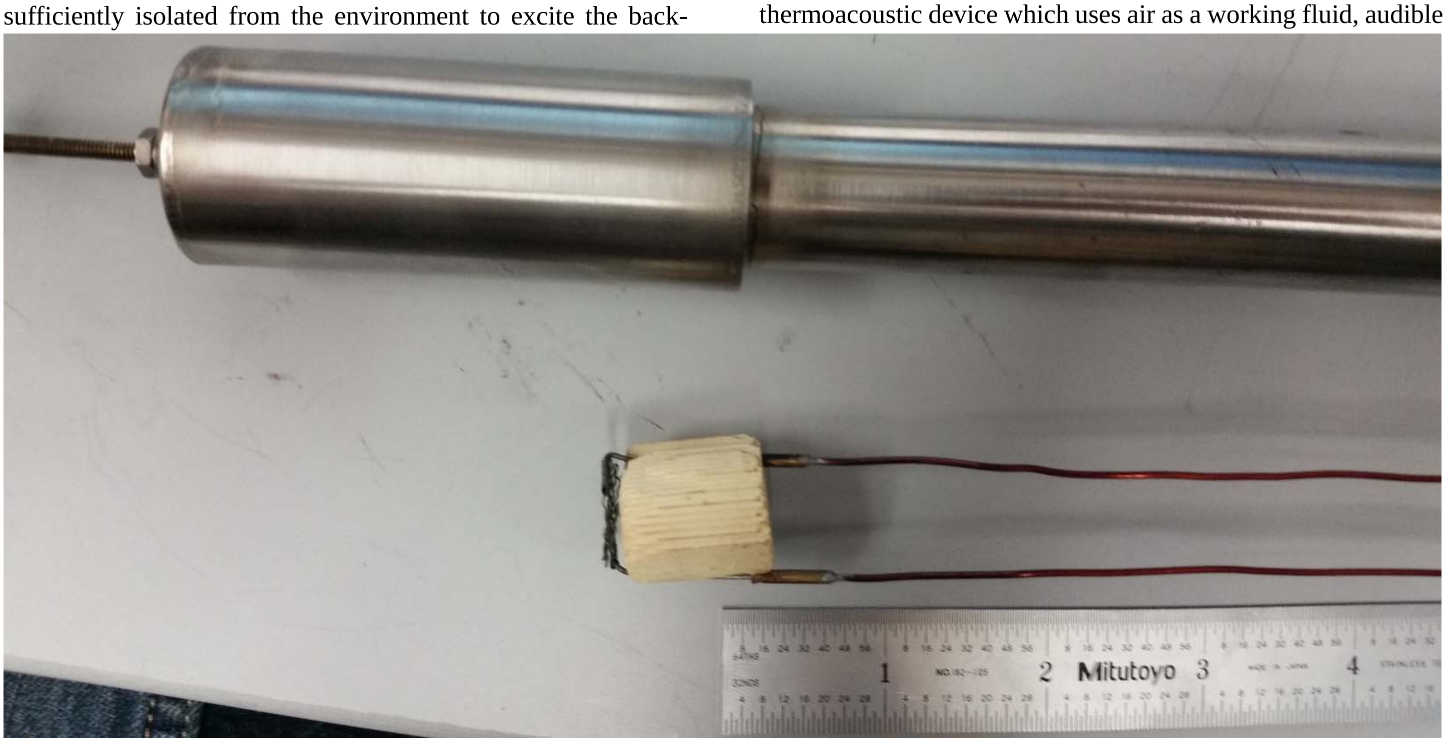

FIGURE 4: TAPS BODY WITH ELECTRICAL HEATER WIRE AND STACK, NEXT TO SCALE.

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sound waves would propagate directly to an observer's ear without a change in medium. However, in a sealed resonator, the propagation medium changes – the fluid inside the resonator is physically separate from the fluid outside the resonator.

Thermoacoustic sound generated inside a sealed resonator is transferred to the surrounding fluid by vibrational motion of the resonator body. When the fluid inside a TAPS resonator moves, it has momentum (by virtue of translational kinetic energy). By the principle of conservation of momentum, an equal and opposite impulse must counter the fluid momentum. In a TAPS, the equal and opposite impulse is provided by the TAPS body – it undergoes rigid-body motion, with momentum opposing the magnitude and direction of the moving fluid's momentum. A set of vibration isolation springs (as seen schematically in Fig. 1, and the points of attachment to the stand in Fig. 2) are used to constrain the TAPS to only axial motion, while being compliant enough to allow axial vibration in the TAPS operating frequency range to occur unattenuated. When the TAPS body moves in response to thermoacoustic engine operation, the environmental fluid near the TAPS cylinder endcaps is displaced. This fluid displacement causes acoustic waves to be generated, which propagate into the environment. The source characteristics of a TAPS largely match those of an acoustic dipole. In a nuclear reactor, it is these environmental fluid waves which travel through the reactor coolant and couple to the vessel walls for measurement by the receiver array.

In summary, vibration transfer from a TAPS to its surrounding fluid occurs by the following process: (1) the hot and cold heat exchangers, interacting through the stack, cause motion of the internal TAPS fluid; (2) the momentum of the moving fluid inside the TAPS must be countered with an equal and opposite impulse acting from the TAPS body; (3) the external fluid near the TAPS endcaps is displaced by TAPS body motion, causing the propagation of sound waves through the surrounding environment and into the reactor vessel.

4.5 TAPS Structural Mass and Working Fluid Selection

The amplitude of TAPS-generated sound waves is dependent on the momentum of the internal thermoacoustic working fluid; as the momentum of the working fluid increases, the amplitude of TAPS cylinder motion becomes greater, and the sound propagated into the environment becomes louder. For these reasons, it is advantageous to minimize the mass of the TAPS body and maximize the mass of the oscillating fluid. In other words, reducing the TAPS body mass will result in larger TAPS body displacement, and increasing the internal fluid mass will result in larger oscillatory force acting upon the TAPS body.

From this physical perspective, selection of the working fluid inside the TAPS has a significant impact on the amplitude of vibrations generated by the resonator. However, selection of the working fluid is first and foremost constrained by the requirements for thermoacoustic engine operation. The fluids used in thermoacoustic systems tend to be noble gases, which are advantageous for several reasons. Noble gases exhibit high thermal conductivity as compared to air, which aids heat transfer between the stack and the fluid undergoing thermoacoustically-induced motion, and ultimately results in the generation of louder sound waves. Noble gases also have minimal chemical reactivity (extremely important in the event of a leak), behave in the simple manner prescribed by the ideal gas law, and in the case of a gas such as a mixture of helium and argon, have exceptionally low Prandtl numbers, which aids thermoacoustic heat transport, and results in a higher heat engine efficiency [6].

In order to achieve high forces (and thus large-amplitude sound output), thermoacoustic engines are typically pressurized with ideal gas mixtures on the order of 10^6 or 10^7 Pascals. The additional thermoacoustic-compatible fluid mass results in increased momentum during engine operation, and greater sound output. Garrett et. al. suggested [3] that the use of different mixtures of helium and argon to "assign" the baseline frequency of each TAPS in a TAPS array would allow frequency multiplexing of each sensor with the same physical hardware – a shift in the gas molecular mass shifts the speed of sound in the resonator, changing the "baseline" frequency of the TAPS according to Eq. 1. While the resonator under examination in this paper was filled with air at atmospheric pressure instead of a more advanced gas mixture at high pressure, the modeling methods to be developed in the following sections are intended to be applicable for any arbitrary working fluid and hardware.

5. LUMPED-PARAMETER THERMAL MODEL

As mentioned in previous discussion about the hot end of the TAPS, the heat generated by a nuclear (or in the experimental hardware in this investigation, electrical) power source can leave the hot end in two ways: along a thermoacoustically-productive path; and along nonthermoacoustic paths. In order to predict both the minimum heat input required for thermoacoustic engine operation and the amount of heat which travels along a thermoacoustically-productive path, Garrett et. al. developed a static lumped-parameter thermal model of a TAPS intended for testing in a nuclear reactor [3]. This model included three parallel paths by which heat could leave the hot end of the TAPS: (1) through thermoacoustic action along the stack, which is subsequently transferred to the cold end of the resonator; (2) heat transfer along the resonator walls to the external coolant; and (3) heat transfer through the insulated cap.

The lumped-parameter thermal resistance model used for analysis of the TAPS discussed previously is shown in Fig. 5. The leftmost path, including the series resistances of the stack, the cold gas, and the tube wall, is thermoacoustically productive. The other two branches of the resistance model can be considered "heat leak" paths. All resistances in this model are conduction resistances, with the exception of the electromagnetic (EM) resistance, which represents radiative heat transfer from the heat exchanger to the walls of the TAPS hot end. As described in [3] for the helium-argon filled resonator and verified for the air-filled TAPS under test, the fluid conditions in the TAPS prevent significant free or forced convection from taking place – all heat transfer in this model is in the form of conduction and radiation.

The thermal resistance values shown in Fig. 5 were calculated using a standard thermal resistance treatment, as

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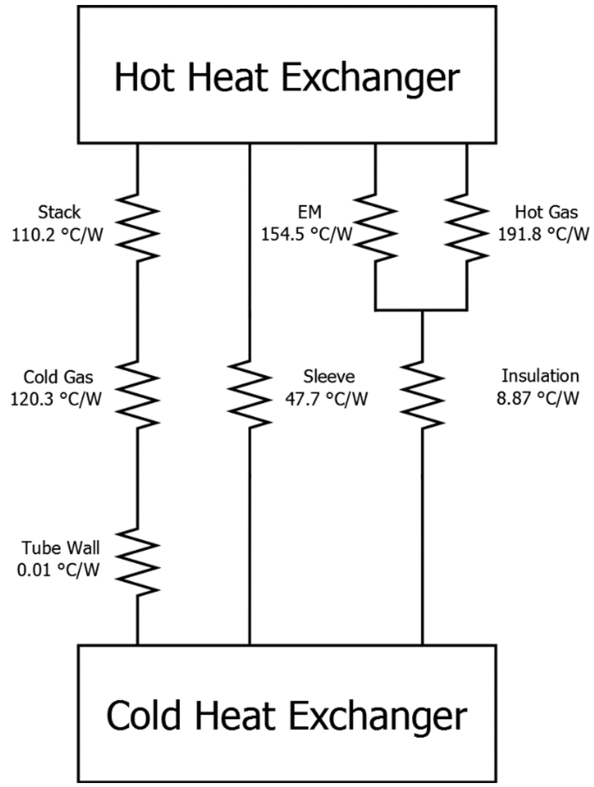

FIGURE 5: TAPS THERMAL RESISTANCE MODEL

would be found in Bergman, et. al. [7], and with the geometry and material properties of the specific TAPS resonator in use. The cold and hot gas conduction resistances, in specific, were found using a 2D conduction relationship, while the stack, tube wall, sleeve, and insulation resistances were calculated using a one-dimensional plane wall treatment. While the left-hand thermoacoustic path and the center sleeve path rely on conduction of heat from the hot heat exchanger, the insulation-path is dominated by heat transfer via electromagnetic radiation, which can be approximated by the linearized relationship in Eq. 2 below, from [7].

$$R_{EM} = \left[4\sigma\left(\frac{1}{\frac{1-\epsilon_{HX}}{\epsilon_{HX}A_{HX}}+\frac{1}{F_{12}A_{HX}}+\frac{1-\epsilon_{duct}}{\epsilon_{duct}A_{duct}}}\right)T_{HX}^{3}\right]^{-1} \qquad (1)$$

In computing the heat transfer resistance due to radiation in Eq. 2, the standard Stefan-Boltzmann constant σ, the areas A of the wire heater, and the temperature T of the heat exchanger are used. However, due to the geometry of the hot end and the electromagnetically gray materials present, it is necessary to take into account the view factor F_{12} of the wire heater to the TAPS hot end walls, as well as the emissivity ε of both the wire and hot duct walls. The wire heater/heat exchanger has two faces – one which is visible from the stack side, and one which is visible from the hot duct. Since the hot duct is only exposed to one side of the heat exchanger, the view factor can be approximated as 0.5. The oxidized state of both the resistance wire heater and the inside of the TAPS body tube places the emissivity of both surfaces at approximately 0.8.

Upon analysis of this thermal model via the current-division techniques used in circuit analysis, it is apparent that only 12.1% of the heat entering the experimental TAPS via the electrical heater will be thermoacoustically productive. While this result clearly indicates significant heat leaks which could be improved in future efforts through modifications to the TAPS construction, the engine's ability to produce sound despite the leaks makes the existing apparatus appropriate for experimentation.

6. DELTAEC THERMOACOUSTIC MODEL

The next step in predictively modeling the acoustic signals measured by TAPS receivers on the vessel exterior involves thermoacoustic simulation of the TAPS. DeltaEC software is employed to model the active thermoacoustic path in the TAPS, including heat exchanger elements, a stack, and open space in the resonator in which thermoacoustic fluid vibrates. Overall, the DeltaEC model for the experimental TAPS is similar to the model developed for a helium-argon TAPS in [3]. A thermoacoustic model not only encompasses the geometric structure of the TAPS, in terms of characteristics such as lengths and areas of different components, but also the material properties of the system components and the working fluid.

Computational simulation of the thermoacoustic system is necessary because of the complexity associated with solving the acoustic wave equation and energy conservation equation for complex geometry and thermal profiles. DeltaEC performs an iterative one-dimensional numerical integration of these equations for a specified geometry. In this investigation, DeltaEC is configured to calculate as outputs (1) the frequency of thermoacoustically-initiated vibrations, and (2) the amplitude of these vibrations. The inputs to DeltaEC are: (1) a known thermoacoustically-productive heat input, calculated as 12.1% of the net electrical power input based on the TAPS thermal model; and (2) the heat rejection (exterior coolant) temperature.

While the DeltaEC simulation automatically calculates the frequency of oscillations as one of the "baseline" parameters in the governing equations, obtaining a prediction of the TAPS vibration amplitude is more complex. As described in [1], an internal DeltaEC function known as "F1" maintains a spatial sum of the oscillating force that a rigid pressure vessel would experience due to thermoacoustically-excited fluid momentum. The sum of this force calculation over the entire model is used to calculate the root-mean-square (RMS) oscillatory force acting on the resonator body. Using the mass of the resonator and Newton's Second Law, the RMS acceleration of the resonator body can also be calculated, as can the RMS magnitude of velocity and displacement of the resonator body. (These latter calculations are made using the frequency-domain differentiation, in which multiplication or division of a waveform amplitude by the waveform's circular frequency yields the amplitude of the derivative or integral waveform, respectively.) A prediction of the working fluid's RMS pressure at the resonator endcap is also available from the simulation. The acceleration, velocity, and pressure measurements are of particular value because they can be used to evaluate a TAPS on a test bench prior to use – if direct measurements of acceleration,

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velocity, and internal TAPS pressure match the thermal/DeltaEC predictions for a given heat input, the TAPS under test can be expected to perform as predicted in its intended application.

7. STRUCTURAL-ACOUSTIC MODELING IN ANSYS

The final component in predictive modeling of TAPS signals includes modeling of the interaction of the TAPS with the environmental fluid, structures within the reactor, and the reactor vessel. Since all reactors and possible experimental test vessels have different, complex geometries, the technique of finite-element modeling (FEM) was selected for structural-acoustic modeling. While computationally-intensive, FEM is advantageous as a predictive technique because it maintains general applicability to all possible reactor geometries and materials. A good TAPS modeling methodology should be applicable to as many situations as possible: accurate for both water- and liquid metal-cooled reactors, as well as for reactors from the size of full-scale power plants down to small modular reactors (SMRs). Coupled structural-acoustic FEM has the ability to predict the response of a structure for modally-dominated acoustic systems, in which position and directionality of the acoustic source results in non-uniform sound pressure levels in the fluid. However, the same code can also handle larger acoustic systems, in which the acoustic modes occur at lower frequencies. The overlap of modes results in a diffuse sound field, which has a relatively constant sound pressure level throughout the fluid volume. As with any computational FE code, obtaining accurate simulation results is dependent on proper mesh density as well as accurate idealization of the system forcing and boundary conditions. For commercial scale reactors, many FE nodes would be required to provide sufficient mesh density for accurate results at the frequency ranges of interest. Such analysis requires significant computing resources, which are continually becoming more economical. Despite its computational complexity, the general flexibility of FE modeling to a wide range of systems makes it extremely attractive as a predictive modeler for the scope of this effort: prediction of the measured TAPS signals in a vessel filled with quiescent fluid.

The solid model to be built in ANSYS (Classic/Mechanical APDL) includes geometry for the vessel and for the acoustic fluid in the intervening space. The TAPS, which displaces fluid by virtue of rigid-body motion, is idealized as a source similar to an acoustic dipole; the superposition of two out-of-phase monopole sources, corresponding to the resonator end diameters, separated by a distance corresponding to the length of the TAPS. Since the DeltaEC model provides vibrational amplitude data from the thermoacoustic simulation, the structure of the TAPS, including the stack, heat exchangers, and insulation stack, do not need to be modeled – the simulation is purely structural-acoustic. The vessel and external fluid are modeled according to typical solid modeling guidelines, and coupling between the external fluid, and the vessel is accomplished through the use of fluid-structure interaction (FSI) constraints.

The FE simulation is excited with ANSYS analytic wave sources (AWAVE function). This function can replicate the “classic” acoustic sources such as monopoles, dipoles, and so on that can be found in any acoustics textbook. As can be seen in the 2D sketch of Fig. 6, in which green and blue monopoles are superposed over the TAPS schematic, the forcing scheme used for this simulation includes two analytic, out-of-phase monopoles placed at the locations of the TAPS endcaps. The diameters of these monopoles match the diameters of the resonator and insulation tube endcaps. The superposition of the phase-selected monopoles results in an axially symmetric 3D output wave similar to an acoustic dipole. Each monopole used in this study can be considered a theoretical sphere which expands and contracts according to a prescribed normal surface velocity. Each monopole is assigned a velocity equal to half of the net TAPS body velocity predicted by DeltaEC.

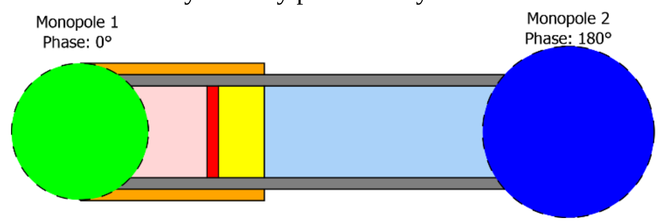

FIGURE 6: SKETCH OF ANSYS MONOPOLE FORCING

A few important pieces of feedback can easily be made available in a controlled, small-scale scenario to validate the model’s applicability to an experiment. DeltaEC results can be compared to direct experimental measurements as the resonator operates – the experimental apparatus to be described in the next section contains a TAPS-mounted accelerometer and pressure sensor for direct characterization of the TAPS output. In addition, the validity of the vessel model can be assessed by comparing the results of a simulated and experimental modal analysis of the test vessel using the mounted network of TAPS receivers. Agreement between the natural frequencies of both analyses indicates an accurate vessel model.

8. EXPERIMENTAL APPARATUS

8.1 Small-Scale Test Vessel and FEM Idealization

In order to validate the TAPS modeling methodology in a controlled environment, a small-scale test facility with acoustic properties similar to those of a nuclear reactor was developed. Most reactor vessels are constructed from stainless steel, and so applying the modeling methodology to an arbitrary 316L stainless steel vessel will realistically test the capabilities of the modeling methodology.

The test vessel used for experiments is shown in Fig. 7. This vessel has a diameter of 26.5 inches (0.6731 meters), an approximate depth of 30 inches (0.6477 meters), and has a thickness of approximately 0.1847 inches (4.7 millimeters). The shallowly domed portion of the bottom head was approximated as a flat surface to simplify modeling. Testing was performed with approximately 24 inches (0.6096 meters) of water inside the vessel, and with the vessel lid open. The TAPS, mounted in its support frame, was suspended from the pictured meter stick in order to minimize the potential for TAPS vibrations to propagate to the vessel walls along a structural path. (Evaluation on an

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FIGURE 7: TEST VESSEL WITH OPEN LID. METER STICK IS USED TO SUSPEND TAPS INSIDE VESSEL.

isolation table revealed that the TAPS spring mounts attenuated structural vibration transfer through the springs by a factor of approximately 10^5. Therefore, it is reasonable to assume that the TAPS spring mounts and suspension in the fluid are sufficient to eliminate any structural vibration transfer.) In its suspended state, the top endcap of the TAPS was located 6 inches (0.1524 m) below the surface of the water.

Every medium through which acoustic waves can travel has a characteristic acoustic impedance, which is the product of the medium's density and the speed of sound propagation through the medium. This acoustic impedance is directly analogous to electrical impedance concepts, which describe how significant wave reflections occur in response to large impedance mismatches. In the case of a room-temperature air-water interface, such as the interface at the surface of the water, the acoustic impedance ratio is approximately 3600. Similarly, the impedance ratio for a steel-air interface is approximately 1.11×10^5. Such large impedance mismatches can be treated as perfectly reflecting boundaries, which is the natural boundary condition for an acoustic medium [8]. For comparison, the impedance ratio at a steel/water boundary is approximately 31, which is indicative of significant fluid-structural coupling. Therefore, the ANSYS model of the vessel leaves the water/air and steel/air boundary conditions in their natural state to reflect these impedance mismatches, while marking all steel/water interfaces as areas where acoustic coupling must be evaluated.

Since the fluid in the vessel is quiescent, full CFD analysis is not necessary to simulate the structural-acoustic coupled model. Instead, elements implementing the acoustic wave equation (with three translational axes and pressure as degrees of freedom) were used to simulate the fluid volume. All geometry was free-meshed with quadratic tetrahedral elements - according to the manufacturer's guidelines, reasonable accuracy is obtained in acoustic simulations when at least six acoustic elements (retaining their midside nodes) are used per wavelength [9]. The free-mesh parameters were refined to ensure solution convergence to a reasonable level of accuracy.

8.2 Sensors/Receivers

The vessel of Fig. 7 was instrumented with a receiver network to measure TAPS vibrations. The specific receivers used were PCB Model 357B61 accelerometers, along with appropriate charge amplifiers and signal conditioners. A subset of these accelerometers can be seen as mounted on the vessel in Fig. 8, in which the opposite side of the vessel shown in Fig. 7 is visible. Each accelerometer has a mass of 30g, which has a negligibly small effect on the natural frequencies of the vessel – no mass loading effects are expected to affect the results of the measurements. The four accelerometers near the center of the figure (above the uppermost reflective heater band) were the primary measurement points used in this experiment.

FIGURE 8: TEST VESSEL WITH RECEIVER NETWORK

The TAPS resonator was instrumented with an Endevco 8510B-5 pressure sensor which directly monitored the pressure of the thermoacoustic fluid inside the endcap. In addition, a PCB Model 608A11/020AC accelerometer was mounted onto the TAPS for direct measurement of TAPS acceleration. These two measurements allow for direct comparison of the experiment and the DeltaEC model, and by association through condition transfer, comparison of the FE model to experimental results.

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8.3 Signal Acquisition and Processing Techniques

All signals from these sensors were monitored using a simultaneous data acquisition system, which consisted of several NI 9215 DAQ modules. All signals were acquired at 50 kHz in approximately 20-second segments.

The captured signals were analyzed using frequency-domain techniques. Specifically, power spectral density (PSD) analysis using Welch's method was used to identify the TAPS vibrational frequency. The cumulative amplitude spectrum (CAS) of each signal, which is the cumulative integral of the PSD, was used to calculate the RMS amplitude of vibration at the frequencies indicated by the PSD. Since all measured signals were sinusoids, the standard factor of the square root of 2 was used to relate true amplitude estimates from simulation and experimental RMS amplitude measurements.

8.4 Test Conditions

Before the TAPS was inserted into the vessel water, experimental modal analysis was carried out with a calibrated impulse hammer to ensure the natural frequencies predicted by the FE model were reasonably close to the natural frequencies of the real vessel. After insertion of the TAPS and initiating thermoacoustic oscillations with the electric heater, TAPS signals were recorded in order to evaluate the accuracy of the predictive modeling methodology. The water in the vessel was held at a constant room temperature of 25 °C.

9. RESULTS AND DISCUSSION

9.1 Experimental Vessel Modal Analysis and ANSYS

Before beginning any type of testing, experimental modal analysis of the water-filled steel vessel was conducted using a PCB Model 086C02 impulse hammer and the receiver network. A typical frequency response function (FRF) is shown in Fig. 9, with a frequency range of approximately 600 to 900Hz.

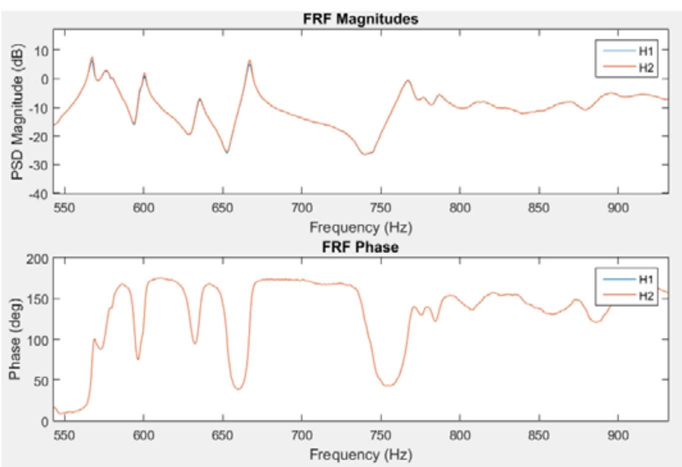

FIGURE 9: EXAMPLE FREQUENCY RESPONSE FUNCTION

From DeltaEC predictions (which will be discussed in the next section), the frequency of the TAPS is known to be near 820Hz. The FRF shows that minimal resonant behavior is present between approximately 800Hz and 875Hz. This is advantageous to experimentation because the impact of resonant effects on the measured TAPS signals will be minimized. ANSYS modal analysis of the vessel model agrees with the experimental modal analysis: solution of the coupled vessel-fluid system indicates the presence of distinct modes at approximately 580, 600, 612, 650, 750, 800, and 870Hz, all of which are visible in this FRF plot. The agreement of the experimental and simulated results suggest that the FE vessel model's geometry and mesh is of reasonable accuracy.

9.2 DeltaEC vs. TAPS Measurements

The thermoacoustic DeltaEC model was evaluated for an electrical power input of 30.65 watts. Based on the static thermal model discussed previously, 12.1% of this power (3.71 W) was directed down a thermoacoustically-productive path. The combined mass of the TAPS and attached sensors was measured at 0.300 kg. A comparison between the simulation and experimental measurements, with error normalized to the experimental value, can be found in Table 1 below.

TABLE 1: DeltaEC and TAPS Measurement Comparison

Quantity	Unit	DeltaEC	Experimental	% Error
Frequency	Hz	821.2	820.6	0.073%
Acceler.	m/s^2_{rms}	3.65	3.58	1.96%
Velocity	m/s_{rms}	0.000708	Not measured	N/A
Pressure	Pa_{rms}	1519	1456	4.33%

The experimental measurements of acceleration, velocity, and pressure are each slightly smaller than predicted. However, the measurements show remarkable agreement with predictions from DeltaEC, with error in amplitude of less than 4.4%. This level of accuracy is achieved despite the lack of dynamic terms in the thermal resistance model, which assist in heat transport down the stack. Minor error is also present in prediction of frequency, although this error is small enough to be negligible – thermal expansion of the tube due to heat from the electrical heater is a possible mechanism for a frequency shift of the observed magnitude.

These results suggest that the TAPS thermal/thermoacoustic modeling methodology has great promise in providing accurate predictions of TAPS output acoustic waves. However, it would be remiss to fail to note that the TAPS thermal resistance model was developed based on the use of "averaged" dimensions and temperature-dependent material properties. In addition, the thermal effects of small elements left over from previous testing, such as embedded thermocouple leads, were neglected in this analysis. While the results from the model presented previously agreed closely with the device under test, the uncertainty in this method remains to be rigorously quantified. For these reasons, future efforts will prescribe the use of more precise component geometry and more advanced thermal modeling techniques to obtain more deterministic thermal models, and therefore reduce the uncertainty in prediction of TAPS output.

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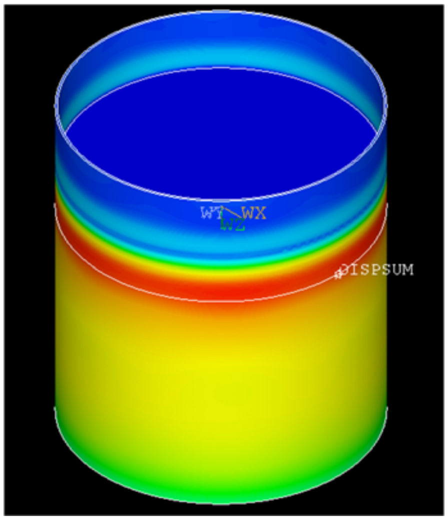

FIGURE 10: ISOMETRIC VIEW OF SYSTEM FINITE-ELEMENT MODEL

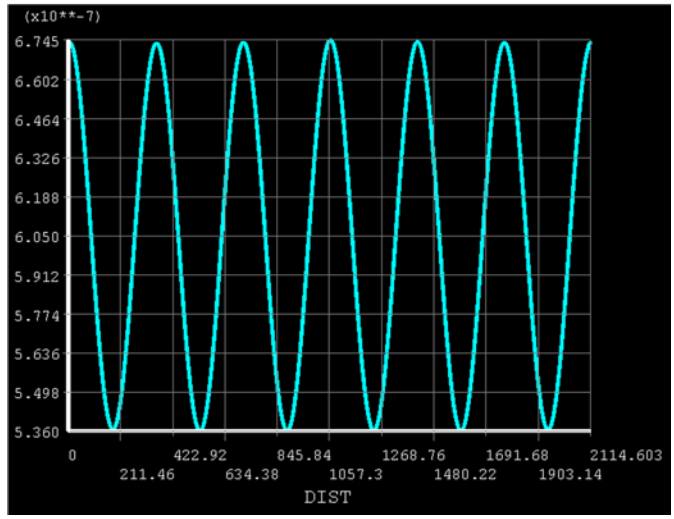

FIGURE 11: PATH PLOT OF PREDICTED RECEIVER LOCATION VIBRATIONS. VERTICAL UNIT IS MILLIMETER.

9.3 FE Models vs. Experimental Data

The final stage of the modeling methodology involves forcing the FE model of the vessel with an acoustic source in order to predict TAPS receiver signals. The acoustic source consists of the two-monopole source discussed previously. Each monopole is excited with the TAPS resonator velocity predicted by DeltaEC: 0.000708 m/s_{rms}, which is a sinusoidal peak-to-peak amplitude of approximately 0.00100 m/s. The solved vibroacoustic model can be seen in an isometric view in Fig. 10, in which red color represents high vibration amplitude and blue color represents low vibration amplitude. This plot clearly shows one high-amplitude vibrational band at the top of the outside wall of the vessel. The four accelerometers used as receivers in this experiment were all located ten inches below the vessel rim: just below the center of the high-amplitude region. The sensors were equally spaced on one-quarter of the total vessel circumference.

In order to examine the simulation results at the location of the accelerometers, a PATH method was used in ANSYS, which resulted in the generation of Fig. 11. This figure displays the net amplitude of vessel surface displacement along the circumference of the vessel at the location of the accelerometers: 10 inches (254 mm) below the top edge of the vessel. (The unit of measure on this figure is millimeters.) The average value of Fig. 11 was used as the mesh convergence criterion. Mesh convergence analysis proceeded until the change in this displacement value stayed below a threshold of $1x10^{-9}$ mm. This threshold is given in the native analysis coordinate system, and is two orders of magnitude below the most significant digit of the result. Given the approximations and free mesh used in generating the FE model geometry for the vessel, the level of uncertainty represented by this criterion is acceptably small.

Some spatial variation in amplitude is present in Fig. 11, which is indicative of a modal-superposition response of the system to input energy. However, the average value of the vibration displacement is clearly near $6.050x10^{-7}$ mm, which was more precisely calculated at $6.051x10^{-7}$ mm via numerical integration of the data in the plot. This average value was used for comparison to the experimental data after conversion to an acceleration prediction using the circular frequency of vibration: the predicted acceleration due to TAPS operation in this experiment was 0.01139 m/s^2_{rms}.

As with the accelerometer and pressure sensor making direct measurements of the TAPS, the amplitude of TAPS-frequency vibrations recorded by the four receiver accelerometers was obtained through use of statistical frequency-domain techniques. In order to compensate for the modal shape of the vessel response as predicted by Fig. 11, the amplitudes of these four measurements were averaged. After signal processing, the wirelessly-transmitted TAPS signal vibration had an amplitude of 0.009763 m/s^2_{rms}. This experimental result is 16.7% larger than the prediction of 0.01139 m/s^2_{rms} (again, with error referenced to the experimental result).

While a 16.7% difference between simulation and experiment may appear to be a large error, this level of agreement between simulation and experiment is quite promising given the time-varying nature of acoustic measurements and the idealizations used in the system model. Most acoustic measurements are considered accurate and stable if fluctuations in the signal level remain within a magnitude change of 1 decibel (dB). The difference between the predicted and measured vibration levels at the accelerometer locations is on the order of 1.34dB. Given the close proximity of these two measurements, and considering the use of a 4-point-average experimental measurement of vessel vibrations, it is reasonable to view the difference between the estimate and measurement to be close to the threshold of discernibility regarding random signal variation: the experimental and predicted levels are very nearly the same.

In addition, it is important to note that, as with the thermal and thermoacoustic models, the idealization of the system used in this analysis surely deviates from the exact system geometry and material properties. All such discrepancies between the model and the true system will introduce mismatch between

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simulation and experiment. For example, the FE model relied on the DeltaEC input amplitude estimates, which were found to be slightly greater than the true amplitude of vibrations - this source of error will have propagated through the model. However, despite these potential sources of error, the close agreement of the modeled results to the experiment suggest that, at least at this scale, the modeling methods developed in this paper are capable of suitable-accuracy TAPS signal predictions, and that future improvements in model determinism will result in more accurate TAPS performance predictions.

10. CONCLUSIONS AND FUTURE WORK

This work seeks to develop models that can predict the external structural response of a structure that contains TAPS sensors. Such a tool, in conjunction with a TAPS array, would permit real-time monitoring of coolant temperature and radiation flux. The predictive methods for analysis of TAPS evaluated in this experiment resulted in TAPS amplitude predictions accurate to approximately 1.5-4.5% of the measured values. Predictions of the level of wirelessly transmitted TAPS signals measured from externally-mounted accelerometers were within 1.4dB of the measured value, which approaches the threshold for discernibility. Frequency prediction was within 0.1% of the true value. When considered in the context of the simplified models used in the analysis, the effects of experimental error, and the time-varying properties of acoustic measurements, these prediction methods are remarkably accurate. Therefore, this experimentation demonstrates that the use of predictive modeling, in the form of condition transfer between a static thermal model, a thermoacoustic model, and a finite element structural-acoustic model, is a viable and accurate method of anticipating the acoustic signals generated by a thermoacoustic power sensor.

The success of this experiment shows that it is possible to predictively model TAPS signals with a high level of accuracy. However, in terms of application of TAPS technology to a full-scale reactor, the models demonstrated in this effort are still relatively basic ones: further modeling methodology development must take place to encompass and correct for the effects of other complications, such as the presence of more complex and other interfering structures, environmental noise from flow and pumps, and thermal gradients and convective effects in the acoustic transmission path. Nonetheless, the results of this experiment show that predictive modeling of TAPS signals is indeed possible, and set the stage for future development of TAPS technology, eventually including the ability to deploy a TAPS array as instrumentation for real-time monitoring of liquid metal-cooled reactors.

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