CHARACTERIZING FLOW INSTABILITIES DURING TRANSIENT EVENTS IN THE TURBINE RIM SEAL CAVITY

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ABSTRACT

Gas turbine engine design requires considerations not only for long-term steady operation, but also for critical transient events. Aircraft engines undergo significant stress during takeoff and landing while power generation turbines must be flexible for hot restarts as renewable energy sources come on and offline. During these transient cycles, engines sustain wear and degradation that can lead to a reduction in the lifespan of their components and more frequent, costly maintenance. Cooling flows are often used to mitigate these effects, but can lead to complex and problematic flow interactions. This study uses high frequency response pressure probes and heat flux gauges in the rim seal cavity of a one-stage research turbine to characterize the properties of large-scale flow structures during transient operation. A continuous-duration turbine testing facility provides the ability to assess the importance of these transients by first reaching steady state operation prior to imposing transient behaviors. Although previous studies have conducted similar measurements for steady purge flows and wheel speeds, varying these parameters to simulate transient effects revealed several unique phenomena not identifiable with discrete steady measurements. The measurement approach connects the varied transient parameter to the behavior of the flow structures to enable a better understanding of the type of instability observed and the root cause of its formation. In particular, a relationship between instability cell formation and rim sealing effectiveness was identified using experimental data and was supported through computational simulations.

NOMENCLATURE

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<thead>
<tr>
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<tr>
<td>b</td>
<td>Hub Radius</td>
</tr>
<tr>
<td>Cp</td>
<td>Coefficient of Pressure, ((P - \bar{P})/0.5p\Omega^2b^2)</td>
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<tr>
<td>f</td>
<td>Frequency</td>
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<tr>
<td>N</td>
<td>Count</td>
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<td>m</td>
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<tr>
<td>P</td>
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<td>Sealing clearance</td>
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<td>T</td>
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<td>ΔT</td>
<td>Driving temperature difference</td>
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<td>t</td>
<td>Time</td>
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<tr>
<td>α</td>
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<td>ε_c</td>
<td>Rim sealing effectiveness</td>
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<td>Φ</td>
<td>Nondimensional purge flow rate</td>
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<td>ν</td>
<td>Kinematic viscosity</td>
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<td>Ω</td>
<td>Angular velocity</td>
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<td>ρ</td>
<td>Density</td>
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<td>Tip clearance</td>
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Subscripts, Abbreviations, and Accents

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<td>Disk</td>
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<td>Heat flux gauge</td>
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<td>Inlet conditions</td>
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<td>max</td>
<td>Maximum quantity</td>
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<tr>
<td>min</td>
<td>Minimum quantity</td>
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<td>Purge</td>
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<td>peak</td>
<td>Maximum value per dataset</td>
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<td>ref</td>
<td>Reference condition</td>
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<td>TOBI</td>
<td>Tangential onboard injection</td>
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<tr>
<td>URANS</td>
<td>Unsteady Reynolds-averaged Navier-Stokes</td>
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<tr>
<td>VTE</td>
<td>Vane trailing edge</td>
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<td>s</td>
<td>Instability cell</td>
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INTRODUCTION

Gas turbine engines are subject to transient events whenever operating parameters such as speed, temperature, or load are varied [1]. Such transient events are present in all gas turbine applications albeit with varying degrees of severity and frequency. In aviation, frequent takeoff and landing operations are required for commercial applications [2] while military engines must respond quickly as the pilot executes evasive maneuvers. In land-based applications, such as power generation, turbines must match the shifting energy demand through the day [3]. As the implementation of renewable energy increased over the past few decades [4], this latter form of transient operation has become increasingly substantial.

There are several thermal effects that result from transient engine operation: metal heat storage, variation of coolant flow fractions, and clearance variations due to thermal expansion [5–8]. The severity of these effects on engine components and subsystems is important to understand in order to ensure appropriate considerations are made during engine design and operation. The thermal effects of transients are most substantial in the hottest sections of the engine – the combustor and turbine. Here, the temperature of the main gas path (MGP) flow exceeds the metal softening temperature of the hardware [9], which requires the use of cooling and sealing flows, also known as purge flows, to ensure safe operation.

In the turbine section, purge flows are used alongside rim seal geometries to prevent harmful ingestion of MGP flow into the underplatform region – a complication that is detrimental to hardware lifespan [1,9]. At intermediate purge flow rates during steady state, the periodic sequence of ingress and egress of MGP flow into the rim seal intensifies [10,11]. Thermal cycling accompanies pressure cycling when ingress-egress patterns are present [10], and this pattern of thermal stress can cause damage to the hardware. In addition to its importance to hardware durability, minimizing purge flow demand is also critical to engine efficiency. The flow is diverted from the compressor, therefore excessively high purge flow demands may result in parasitic efficiency losses; this effect has been approximated as a 1.4% increase in efficiency for a 50% decrease in purge flow rate [12]. For this reason, it is important to understand how the rim seal cavity sealing behaviors during transients.

The majority of studies investigating rim sealing performance are conducted under thermally steady conditions [11,13,14]. Although several studies have examined the effects of transient operation [7,15,16], only one to date has used experimental data to validate their computational models [15]. The present study leverages a continuous-duration test facility to address these gaps in understanding by investigating the influence of transient operation on rim seal characteristics.

LITERATURE REVIEW

Only a limited number of studies have used computational modelling to investigate performance variations during transient events. Nielsen et al. [7] studied transient effects in gas turbine engines by developing a computational model that calculated clearance variation in the secondary air system. May et al. [16] used transient 1D and 2D models to demonstrate that pressure profiles and disk cavity vortices in the disk cavity were dependent on the wheel speed rotational effects. These vortices were also shown to affect the pressure at the radial inlet and outlet of the cavity, but were attenuated by increasing purge flow rate. The model by May et al. used a highly simplified geometry lacking blades and vanes that have been shown to have a significant impact of vortex strength in the disk cavity [17–21].

Berdanier et al. [15] used experimental methods to examine how transient purge flow influenced a variety of engine health related factors such as thermal growth of hardware and sealing effectiveness. While their study used pneumatic pressure taps to evaluate performance, this study expands upon those methods by applying fast response instrumentation that allowed for more in-depth, time resolved analysis. Few studies have endeavored to understand transient phenomenon. Those who have, left much room to explore experimental methods using engine-relevant hardware and conditions.

Although few studies have used experimental validation to examine how the cycles of ingress and egress differ during transient operation, a robust foundation has been established by numerous steady state studies. Many foundational studies have examined the driving forces of ingestion [12,22]. Owen et al. [23] derived analytical solutions for flow between rotating and stationary disks. This analysis led to the categorization of the types of ingestion: rotationally-induced (RI), externally-induced (EI), and combined ingress (CI) [24,25]. Pressure measurements have been commonly used to characterize flow behaviors in the rim seal cavity, and the ability of the purge flow to prevent ingestion is often quantified using rim sealing effectiveness, a property determined by measuring the concentration of a tracer gas. Phadke and Owen [26] used a wheel space low pressure criterion as evidence of ingress, and other papers have connected pressure variation with ingestion and sealing effectiveness [17,27]. The extent of the impact of MGP ingestion is therefore not yet well understood during transient operation.

Large-scale structures caused by fluid instabilities in the rim seal cavity have been identified by several investigations [17,28]. The formation of these instabilities, also referred to as cells, in intermediate purge flow regimes has been linked to an inflection point in the sealing effectiveness curve [11,17,19]. It is theorized that the low pressure caused by the flow structures draws fluid from the MGP in through the rim seal, reducing the effectiveness inside the cavity, creating this inflection point [19]. One of the first to identify these structures was a study by Cao et al. [28], which used experimental methods to verify a computational fluid dynamics (CFD) model. The numerical
solution visualized discrete flow structures and a frequency analysis further characterized these structures to show that they are rotating and are functions of rotor speed.

The large-scale flow structures have been identified under three main classifications: inertial waves [29], Taylor-Couette instabilities [17], or Kelvin-Helmholtz instabilities [30]. Rabs et al. [30] demonstrated that the Kelvin-Helmholtz instability vortex structure, which is generated in the shear layer between two parallel flows of different velocities, could form in the rim seal cavity at the intersection of the ingested flow and the sealing air flow. These cells are important to understand not only because they cause time-varying thermal variations, but because they can decrease the time-steady sealing effectiveness, corresponding to an elevation of hardware temperature over the course of operation. This study will focus on the Kelvin-Helmholtz instability theory about instability cell formation.

Methods have been developed to calculate the properties of these flow structures from multi-channel, fast-response pressure transducers. For example, Beard et al. [31] introduced cross correlating two pressure signals from the rim seal cavity to calculate the speed of the structures as they flow circumferentially about the wheel space. The structures travel consistently at about 80% of the disk speed and the count varies with purge flow rate. Lei et al. [32] found that the speed of the structures decreased slightly with increasing purge flow rate, and concluded that purge flow stabilizes the flow in the cavity. Monge-Concepción et al. [11] examined the effect of flow ingestion on the stability in the rim seal cavity. Their study found that the cell properties calculated from experimental data agreed with the visualization from the quarter-wheel Unsteady Reynolds-averaged Navier-Stokes (URANS) models developed by Robak et al. [33]. The present paper will extend this instability analysis method by applying it to transient operation.

While it has been established that transient operation is particularly damaging to engines [5–9], and many studies have evaluated flow structures at steady purge flow rates or wheel speeds, no other study has used fast response instrumentation to examine the flow structure behavior during transient regimes. Therefore, the purpose of this paper is to address this gap by experimentally exploring rim seal cavity phenomena during transient regimes.

**EXPERIMENTAL METHODS**

This study was conducted at the Steady Thermal Aero Research Turbine (START) Lab at the Pennsylvania State University. Figure 1 depicts the major components of the facility in blue, with the colors of the arrows corresponding to the relative gas path temperatures. The design of the START facility is outlined in detail by Barringer et al. [34], and the transient operation capabilities are discussed by Berdanier et al. [15].

The research facility contains a one-stage turbine test section comprised of real engine hardware and operated in a continuous-duration mode at engine-relevant conditions. The dynamometer installed at the facility allows for steady operation up to 11,000 RPM with speed setpoint stability within ±10 RPM. Supply air for the turbine is provided by two industrial compressors, each powered by 1.1 MW (1500 HP) motors, capable of a combined airflow of up to 10.4 kg/s (25 lbm/s) with an outlet pressure of 480 kPa (70 psia) and nominal outlet temperature of 380 K (220°F). The majority of the flow from the compressors continues into an in-line natural gas heater positioned upstream of the turbine. The combustor burns natural gas and has a maximum capability of 672K (750°F), although the facility was operated at a lower temperature in this study.

Approximately 10% of the flow is diverted from the MGP before it enters the combustor. This flow is cooled to 273K (32°F) using a shell-and-tube heat exchanger and it then can be distributed to several injection points throughout the stage, each of which is independently controlled and metered. For this study, only purge flow was evaluated, as depicted by the blue arrow in the cross-section view shown in Figure 2. The purge flow cools the wheel space and prevents hot MGP ingress into the rim seal cavity. This purge flow is injected into the vane underplatform region through 150 equally-spaced holes distributed around the hardware. The facility is also capable of using the redirected flow...
as Vane Trailing Edge (VTE) flow and Tangential On-Board Injection (TOBI) flow, but neither were used in this study.

**Facility Instrumentation**

Experimental data for this study were collected using fast-response sensors installed in two additively-manufactured vanes. The data collected from fast response pressure transducers, heat flux gauges (HFG), and tip clearance probes were sampled at a nondimensional sampling frequency of \( f/ f_0 \approx 600 \), where \( f \) and \( f_0 \) represent the data sampling rate and the disk frequency, respectively. A low-pass filter was also applied to prevent aliasing. The calibration of these fast response pressure transducers is described in detail by Siroka et al. [10]. Six pressure transducers were installed in the rim seal cavity at radial installation locations shown by the blue circular marker in Figure 2 and the circumferential location shown in Figure 3. The fast response pressure sensors were distributed with equal spacing across one vane pitch, and a subset of the measurements were used for the present analysis.

This study also used the fast response temperature signal collected by one single-sided thin film HFG at the same radial location in the rim seal region, as depicted by the red triangle in Figure 3. Other property measurements such as flow rates, speeds, temperatures, and pneumatic pressures were read using the main data acquisition system with data save rates of 1 Hz.

Rim sealing effectiveness is quantified by seeding the purge flow with a supply concentration, \( c_s \), of 1% \( \text{CO}_2 \). Total pressure probes with Kiel heads were installed at the turbine vane inlet to measure the nominal \( \text{CO}_2 \) concentration at the turbine stage inlet, \( c_n \). Further concentration measurements, \( c \), were collected at various radial locations within the rim seal for comparison. The rim sealing effectiveness, defined by Equation (1):

\[
\varepsilon_c = \frac{c - c_\infty}{c_s - c_\infty}
\]

is fundamentally bounded between 0, where the flow is entirely sourced from the MGP, and 1, where the flow is entirely sourced from the purge flow. Effectiveness values reported in this study were previously presented by Monge-Concepción et al. [35]. The methodology of quantifying effectiveness using gas tracing has been studied at length in literature [18,27] and has been previously reported by the START lab [10,11,13,14,36].

**Turbine Steady and Transient Operating Conditions**

The data represented in this study were collected under primary operating conditions identical to Berdanier et al. [15] as described in Table 1. The purge flow rate is presented in nondimensional form, \( \Phi_p/\Phi_{ref} \), where \( \Phi_p \) is the measured nondimensional purge flow rate as described in Sangan et al. [37], and \( \Phi_{ref} \) is the nondimensional purge flow rate at which the cavity at the coolant injection plane is fully sealed.

In addition to its primary focus as a steady research turbine, the continuous-duration nature of the START facility creates a unique ability to collect transient operation data for a number of parameters. Transient parameters of particular interest that have been evaluated in the past include purge flow rate, wheel speed, MGP temperature, and TOBI blade flow. For the purposes of this study, the response of the system to transient purge flow rate and wheel speed was characterized.

For transient purge flow operation, as depicted in Figure 4, the entire system was initially brought to thermally steady conditions at the zero-purge-flow operating condition. The purge flow rate was then increased to a high-flow condition over 90 seconds by opening the flow control valve from fully-closed to its fully-open position. The end state for the valve opening is user-defined; for this study, the high-flow condition always exceeded the purge flow required to achieve a fully-sealed condition in the rim seal. After the initial transient period, the

![Figure 3. Diagram of a vane doublet showing the circumferential location of fast response probe installations.](image-url)

![Figure 4. Transient nondimensional purge flow as function of time.](image-url)

Table 1. Operating Conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Blade Inlet Axial Reynolds Number</td>
<td>( \text{Re}_x )</td>
<td>( 1.4 \times 10^5 )</td>
</tr>
<tr>
<td>Rotational Reynolds Number</td>
<td>( \text{Re}_\Omega )</td>
<td>( 3.5 - 6.0 \times 10^6 )</td>
</tr>
<tr>
<td>Density Ratio</td>
<td>( \rho_p/\rho_{MGP} )</td>
<td>( 1.0 - 2.5 )</td>
</tr>
<tr>
<td>Nondimensional Purge Flow</td>
<td>( \Phi_p/\Phi_{ref} )</td>
<td>( 0 - 1.5 )</td>
</tr>
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</table>
system was again allowed to thermally soak at the high purge flow condition. This same procedure was followed in reverse for the decreasing purge flow transient operation, which enabled the characterization of hysteresis patterns. A more in-depth description of this procedure, transient thermal growth considerations, and their associated effect on hysteretic seal performance was reported by Berdanier et al. [15].

Similar to the transient purge flow tests, transient wheel speed operation started by achieving steady state conditions at a reduced wheel speed of 7,000 RPM. The rotational speed was then manually increased at a fixed ramp rate up to a high-speed condition just below the 11,000 RPM facility maximum (to maintain sufficient safety buffers). After the initial ramp up of speed, the system was allowed to reach a steady state condition at the high-speed condition before passing through a fixed ramp rate decrease to the original reduced-speed condition. For consistency, the ramp rate was maintained at approximately 700 RPM per minute for both increasing and decreasing trials.

Measurement Uncertainty

All measured parameters inherently include bias and precision uncertainty. Table 2 shows the measurement uncertainty for turbine operating parameters and instrumentation. The uncertainty calculation method applied to all data and calculations contained within this study is described in Figliola and Beasley [38]. The data are presented using normalized pressure $P'$, temperature $T'$, nondimensional frequency $f/f_D$, normalized cell speed $(\Omega_D/\Omega_B)$, and cell count (Ns). This paper follows the normalization method established by DeShong et al. [39] for pressure and temperature data, which are presented as self-normalized differences using the minimum and maximum values from the transient purge flow rate dataset. This normalization procedure is defined in Equation (2).

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

Table 2: Measurement Uncertainty

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<td>Inlet Temperature</td>
<td>$T_m$</td>
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<tr>
<td>Time-resolved Pressures</td>
<td>$P'/P_{\text{ref}}$</td>
<td>$\pm$ 0.030 to $\pm$ 0.127</td>
</tr>
<tr>
<td>Time-resolved Temperatures</td>
<td>$T'/T_{\text{ref}}$</td>
<td>$\pm$ 0.005 to $\pm$ 0.021</td>
</tr>
<tr>
<td>Sealing Effectiveness</td>
<td>$\varepsilon_c$</td>
<td>$\pm$ 0.015 to $\pm$ 0.025</td>
</tr>
<tr>
<td>Rotor Tip Clearance</td>
<td>$\tau/r_s$</td>
<td>$\pm$ 0.0001</td>
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Nondimensional Transient Purge Flow

Previous studies investigating rim sealing have primarily used the nondimensional purge flow rate $\Phi_p$ when detailing the independent variable, which was derived as a function of nondimensional flow rate, seal clearance ratio, and rotational Reynolds number [24,25,37,40]. As shown in Equation (3), $\Phi_p$ is a function of purge flow rate, seal clearance, density, rotational velocity, and radial location:

$$\Phi_p = \frac{\dot{m}_p}{\rho \Omega_b b^2}$$

where $\dot{m}_p$ is the purge flow rate, $s_c$ is the sealing clearance, $\rho$ is the density, $\Omega_b$ is the disk frequency, and $b$ is the hub radius. The parameter $\Phi_p$ is derived from an orifice model, which includes an analytical solution and has demonstrated agreement with experimental data. Nondimensional purge flow rate $\Phi_p$ is proportional to purge flow rate $\dot{m}_p$ for specified seal geometries and operating conditions, therefore they can often be used interchangeably, and relationships such as $\dot{m}_p/\dot{m}_{\text{ref}}$ and $\Phi_p/\Phi_{\text{ref}}$ are equivalent; this equivalence is however only valid for thermally-soaked steady state operation. For transient operation, several studies have shown that clearance varies [5–7,15]. For this study, the seal clearance was not measured directly, but was estimated using Equation (4) [15]:

$$s_c = r_{1a} + r_{s,10} \alpha (T_2 - T_{\text{ref}}) - (\tau - \tau_{10})$$

where $r_{1a}$ is the design rim seal clearance, $r_{s,10}$ is the initial value, $\alpha$ is the coefficient of thermal expansion, $T_2$ is the measured metal temperature, $T_{\text{ref}}$ is the initial temperature at the beginning of a transient event, $\tau$ is the measured blade clearance, and $\tau_{10}$ is the initial clearance. The nomenclature $T_2$ is used for consistency with Berdanier et al. [15]. The first term in this equation accounts for the initial seal clearance, the second accounts for dimensional changes of the stator due to thermal expansion, and the third approximates the thermal growth of the rotor, as defined in Berdanier et al. [15].

During transient operation, the changing seal clearance behavior dictates $\Phi_p$, which was calculated for this study using non-constant values of $\rho$ and seal clearance $s_c$ as shown in Equation (4). As previously identified, the calculation of $s_c$ is dependent on the selection of temperature for use in Equation (4) [15]. For this reason, the corresponding effect of temperature selection and its influence on relationships between $\dot{m}_p/\dot{m}_{\text{ref}}$ and $\Phi_p/\Phi_{\text{ref}}$ were evaluated.

Two options were considered for the selection of the temperature variable, corresponding to two locations in the underplatform region. The impacts of, and supporting justification for, calculating the sealing clearance using one of these two temperatures is described in Berdanier et al. [15].

Figure 5 depicts the radial locations of the two temperature sensor options as well as the resulting $\Phi_p/\Phi_{\text{ref}}$ for the preferred temperature measurement. A pattern of hysteresis is shown between the two transient trials with the steady data closely following the decreasing purge flow rate trial data. Based on this behavior, the decreasing purge flow trial is a better approximation of thermally-soaked steady state conditions, due to the system reaching steady state at maximum purge flow conditions. The calculation method shown in Figure 5 using the inboard temperature location $T_2$ is used for the remainder of this paper.
as it reflects a matched relationship between the decreasing transient trial and the steady data.

**TEMPERATURE HYSTERESIS EFFECTS**

An important parameter that dictates thermal lag and flow behaviors in the rim seal cavity is the temperature difference between the MGP and the purge flow, as defined in Equation (5).

\[ \Delta T = T_{MGP} - T_p \]  

(5)

Figure 6 shows the behavior of the driving temperature difference \( \Delta T' \) normalized using the scheme defined in Equation (2) during the increasing, decreasing, and steady purge flow rate trials. These hysteresis effects are representative of the thermal lag that would also be present during transient events in true-scale engine operation.

The increasing trial has a very low \( \Delta T' \) because it starts from a zero-purge operating condition. The purge supply hardware was allowed to come to a high steady state temperature because there was no purge flow to cool it. As the purge flow is increased, the hot hardware transfers heat into the purge flow before it reaches the disk cavity, which greatly decreases the temperature differences between the purge and MGP flows.

After the end of the increasing purge flow, the system is maintained at the maximum purge flow condition and allowed to reach steady state again. During that period, the hardware cools to its minimum temperature. When the purge flow is subsequently decreased, the cool hardware acts as a heat sink and the \( \Delta T' \) remains high even at low purge flow rates. This thermal lag can be observed when comparing the steady state points in Figure 6 to the transient operation lines. The \( \Delta T' \) of the steady and decreasing trial data far exceed that of the increasing trial data because the system is nearly thermally soaked during the decreasing trial while the steady purge condition is completely thermally soaked. At low purge flow rates, however, the steady \( \Delta T' \) is exceeded by the decreasing purge transient, as the hardware does not have enough time to heat up to match its temperature under thermally-steady conditions. The same analysis shown in Figure 6 was also performed for transient wheel speed trials, but those trials exhibited negligible thermal lag and therefore \( \Delta T' \) is constant with respect to RPM.

The behavior identified in Figure 6 further influenced the selection of parameters used to calculate \( \Phi_p \) - the steady data in Figure 5 aligned with the decreasing trial when \( T_2 \) was used to calculate \( s_C \) and did not when it was calculated using \( T_1 \). To most appropriately represent the system, an accurate hysteretic relation must be preserved.

**UNSTEADY PRESSURES AND ANALYSIS**

Fast-response pressure and temperature sensors were used to capture the highly unsteady behavior of the Kelvin-Helmholtz-like instabilities present in the rim seal cavity observed in literature [10,17,30,32]. Previous studies have used the coefficient of pressure, \( C_p \), whereby the pressure signal is nondimensionalized using the dynamic pressure \( [10,11,35] \). Dynamic pressure is a function of tangential velocity and is varied during the transient wheel speed tests. Using a non-constant parameter to nondimensionalize the data alters the trend in the time-resolved signals. To compare the pressure and temperature trends independently for transient purge flow rate and wheel speed, a constant variable was used for the nondimensionalization according to Equation (2).

Figure 7 shows the normalized, time-resolved pressure and temperature signals for a single revolution at \( \Phi_p/\Phi_{ref} \approx 0.7 \). The time series data Figure 7 have been filtered using a low pass filter to exclude the blade passing frequency, as described by Monge-Concepción et al. [11]. Through this approach, the periodic behavior in Figure 7 indicates cell passing events.

The superimposed fast-response temperature data plotted in Figure 7 are also phase-shifted by approximately half a period relative to the pressure data. The cycles of low- and high-pressure during ingress and egress respectively are associated
with cycles of high and low temperature – a phenomenon that was first identified by Siroka et al. [10].

Using the time-resolved data, the unfiltered pressure and temperature signals were processed using the procedure outlined in Figure 8. This procedure generates a spectrogram-style plot, which is commonly used as an exploratory tool in acoustical analyses for transient processes. From the spectrogram-style plots, the dominant frequency and maximum amplitude are extracted as functions of the transient variable.

Using the method established by Beard et al. [31], the dominant frequency as well as the phase lag between two signals can be used to calculate cell properties, such as speed and count. The phase lag is calculated using the cross correlation of two sensors of a known spacing, and is equivalent to the cell travel time between the two sensors.

**TRANSIENT FREQUENCY DOMAIN ANALYSIS**

A comparison of steady to transient data from a transient purge flow test where wheel speed is kept constant just below the 11,000 RPM facility maximum is provided in Figure 9. The steady data studies that examined effects of purge flow rate similarly applied a Fast Fourier Transform (FFT) but did so to a dataset that spanned numerous revolutions. This method for the steady data [11], shown in the solid lines in Figure 9(a), results in much narrower frequency bins and a more discrete dominant pressure frequency peak than in the case of the transient data.

When the FFT is applied only to a single revolution of data, the resulting frequency bin size is wider due to the shorter time series length. This effect is visible in the dashed lines in Figure 9(a), where an FFT was applied individually to 500 revolutions of data with the resulting spectral values being ensemble averaged. Despite the wider lobes, the peak is centered at the same frequency, as is expected. It should also be noted that the two datasets featured in Figure 9(a) were normalized using local maxima and minima, so the amplitudes are not intended to be a point of comparison.

Figure 7. Fast response pressure and temperature signals for one revolution at $\Phi_p/\Phi_{ref} = 0.7$.

For the purposes of a transient analysis, there may be changes occurring between revolutions, so applying an FFT to the entire dataset does not allow for detection of such events. In Figure 9(b), the revolution-by-revolution FFT method is applied to a transient dataset at a selection of discrete purge flow rates matching the steady dataset. Qualitatively, the transient frequency spectra in Figure 9(b) are nearly identical to the dashed lines in Figure 9(a), which shows the similarity between the transient and steady data at equivalent nondimensional purge flow rates. Therefore, when analyzing the transient datasets, each revolution can be assigned a discrete value, and the FFTs may be displayed together as function of the transient parameter in the style of a spectrogram plot.

For brevity, only the increasing transient purge flow rate data sourced from the fast response pressure sensors is plotted in Figure 10. The dark region spanning from $0.9 < \Phi_p/\Phi_{ref} < 1$ represents a time period where no data was collected due to a limitation in the data acquisition method. Notably, there is an abrupt shift in the dominant frequency at $\Phi_p/\Phi_{ref} \approx 0.7$. Although initially appearing discontinuous, this transition takes place over
The dominant frequency near $f/f_D \approx 5$ shown in Figure 10 represents the number of times per revolution an instability cell passes a sensor in the rim seal cavity. This cell passing rate is visible in the waveform data shown in Figure 7, where there are approximately five periods in both the fast response pressure and temperature signals. The shift in this frequency illustrated by the spectrogram indicates that the number of cells passing the sensor per revolution has shifted. The shift can be due to changes in either the speed at which the cells were rotating or the number of cells distributed about the casing. The secondary frequency peak near $f/f_D \approx 10$ represents a harmonic of the fundamental frequency identified at $f/f_D \approx 5$.

Results in Figure 11 are extracted from the spectrograms for all transient test conditions. Figure 11 also depicts the relevant distinguishing features between datasets for steady and transient conditions including both increasing and decreasing purge flows. Furthermore, data collected using fast response pressure transducers are shown in Figure 11(a,b) and using fast response temperature sensors are shown in Figure 11(c,d).

The maximum amplitude in Figure 11(a) from both the transient purge trials, in Figure 11(c) for the decreasing purge, and the dominant frequencies in Figure 11(b,d) from both the transient trials fall within the range bars from the steady state data collected by Monge-Concepción et al. [11] and Siroka et al. [10] for the fast response pressure and temperature data respectively. Hysteresis is observed between the increasing and decreasing transient purge flow rate trials as shown in Figure 11, where the maximum $P'$ amplitude for increasing purge data is reached at a lower relative purge flow rate than for the decreasing purge case. In Figure 11(a), all three datasets align at low purge flow rates, but the transient data for the increasing purge case diverges at high purge flow rates from both the steady and decreasing transient data. Berdanier et al. [15] concluded from low-frequency pressure measurements that effectiveness is higher in an increasing, transient purge flow regime compared to a steady regime. This effect is due to thermal expansion in the blades during a transient process that starts with minimal cooling flow creating a smaller sealing clearance, and thus requiring less flow to seal, reaching a fully purged condition at a lower purge flow rate. In Figure 11(a), there is some hysteresis between the increasing and decreasing purge flow trials, where the amplitude of the increasing trial drops off at a lower purge flow rate than the decreasing trial. Specifically, the increasing trial reaches the same amplitude at $\Phi_p/\Phi_{ref} \approx 0.8$ that the decreasing and steady trials do at $\Phi_p/\Phi_{ref} = 1.0$, which is consistent with the findings from Berdanier et al. [15]. Also featured in Figure 11(b), the dominant frequency shift and the high-variability frequency region associated with the amplitude decline ($\Phi_p/\Phi_{ref} > 1$) both occur at slightly lower purge flow rate in the increasing trial than in the decreasing trial.

The dark region in the dominant frequency at $\Phi_p/\Phi_{ref} < 0.4$ in Figure 10 does not correspond to missing data, but rather to a signal with a very low amplitude and therefore a low signal-to-noise ratio (SNR). The correspondence can be noted in the same $\Phi_p/\Phi_{ref}$ range in Figure 11(a) and Figure 11(b).
For the temperature measurements in Figure 11(c), there is significant hysteresis between the transient increasing purge flow case compared to the steady and decreasing purge flow cases. While the decreasing and steady purge cases show the same behavior as Figure 11(a), the increasing case shows a much lower amplitude of $T'$. Meanwhile, the decreasing purge data shows good agreement with the steady data at high purge flow rates, but diverges at purge flow rates $\Phi_p/\Phi_{ref} < 0.75$. Both of these divergences are due to thermal lag in the system.

The hysteresis between the two transient cases in Figure 11(c) is due to the driving temperature difference $\Delta T$ between the MGP and purge flow temperatures, as defined in Equation (5) and depicted in Figure 6. The discrepancy between increasing and decreasing trials in Figure 11(c) could be interpreted as a different ingestion behavior. However, it is important to point out that the pressure data, Figure 11(a) were collected simultaneously with the temperature data, Figure 11(c). Therefore it is known that the flow behavior creating the trend in the increasing purge case in Figure 11(a) is also occurring in Figure 11(c), but is not being detected. While the pressure in the cavity cycles between high pressures during egress and low pressures during ingress, there is an analogous occurrence between thermal cycling of low temperature during egress and high temperature during ingress, as depicted in Figure 6. However, if the MGP and purge flows are approximately the same temperature, the fast response temperature sensor is unable to distinguish ingress from egress because the ingress and egress flows are the same temperature, so the SNR is insufficient.

Conversely, as shown in Figure 6, the driving temperature difference from the decreasing purge flow case exceeds that of the steady case at low purge flow rates. The consequence of this relation is identified explicitly in Figure 11(c), where the maximum amplitude of the decreasing purge flow rate trial agrees with the steady data at high purge flow rates, but exceeds the steady data at low purge flow rates.

Due to the low amplitude from the increasing purge and the resulting low SNR, the frequency data in Figure 11(d) for the increasing purge is dominated by noise. However, the decreasing purge data and the aforementioned dominant frequency shift agree with the fast response pressure signal results in Figure 11(b). This consistency demonstrates that the unsteady phenomenon can be detected by both pressure and temperature sensors in the time and frequency domains.

The data from the transient wheel speed case is shown in Figure 12. In these tests, constant dimensional purge flow rate was set to match the nondimensional purge flow rate of $\Phi_p/\Phi_{ref} = 0.7$ from the transient purge flow tests. Unlike the transient purge cases, the transient wheel speed case as does not exhibit any abrupt shifts in the dominant frequency. Additionally, both the datasets result in qualitatively identical plots because they were collected concurrently from the two sensor types and captured the same phenomenon. For the sake of brevity, only the

Figure 11. The (a,c) maximum amplitude and (b,d) dominant frequency during a transient purge flow test from fast response pressure sensor (a,b) and temperature sensor (c,d) data respectively.
pressure data for the increasing transient wheel speed trial are shown in Figure 12.

When the maximum amplitude and dominant frequency are extracted from the spectrograms and shown in Figure 13, a repeatable, low variation trend in both the maximum amplitude and dominant frequency emerges. Similar to prior data presentations, the values in Figure 13(a) were normalized relative to the minimum and maximum transient purge flow trial values, so as to emphasize the relatively low amplitude variability compared to the purge flow transients in Figure 11(a). The lack of similar hysteresis effects seen in Figure 11(c) for the transient wheel speed cases in Figure 13(c) is due to negligible variation in the driving temperature difference as a function of wheel speed. As previously stated, there are no abrupt shifts in the dominant frequency in either Figure 13(b) or Figure 13(d), but rather a linear, downward trend.

**TRANSIENT INSTABILITY CELL PROPERTIES**

Previous studies that have used frequency domain analysis to calculate instability cell properties focused on steady state operation. The current study provides the ability to use the same method for the transient purge data. The time required for a cell to pass between sensors is determined by cross correlating the signals of two sensors some known angle apart. It should be noted that this analysis was only conducted using the fast response pressure sensors. Of the fast-response temperature sensors installed, only one was able to provide usable data. This calculation requires two signals and therefore this calculation could not be conducted on the temperature data. Similar to past studies, the time lag (Δt) and angle of separation (α_k) are combined in Equation (6) to calculate cell speed [11,31].

\[
\Omega_s = \frac{\alpha_k}{\Delta t}
\]

The cell speed \(\Omega_s\) normalized by disk speed \(\Omega_D\) is shown in Figure 14 as a function of transient purge flow rate. The cell properties are functions exclusively of data depicted in Figure 7 and Figure 11(b). It has already been established that the steady data aligns with the transient data, therefore it is also appropriate to conclude that the calculated cell properties agree between the steady and transient datasets. As previous studies have reported, \(\Omega_s\) decreases with increasing purge flow rate [11,32]. This functional relationship indicates a high purge flow stabilizes the rim seal cavity when it is nearly fully purged. As the flow stabilizes at high purge flow rates, the deceleration of the cell speed approaches zero, thereby resulting in a constant value with respect to \(\Phi_p/\Phi_{ref}\). This steadily declining cell speed begins in Figure 14 after a threshold of \(\Phi_p/\Phi_{ref} \approx 0.4\). However, the values preceding this threshold are not true estimates of cell speed, due to the low-amplitude pressure signals resulting in an unreliable cross-correlation.
As an additional metric assessing cell behavior, Equation (7) uses the calculated cell speed with the dominant frequency \( f_{\text{peak}} \) to calculate the number of cells, \( N_s \).

\[
N_s = \frac{2\pi f_{\text{peak}}}{\Omega_s}
\tag{7}
\]

The number of cells is overlaid with the time-steady sealing effectiveness as a function of \( \Phi_p/\Phi_{\text{ref}} \) in Figure 15.

An advantage of the presented transient analysis method is the ability for properties to be observed over a continuous variable. In Figure 15, the cell count, \( N_s \), is split into three separate regimes: Region (I) low and noisy at low purge flow rates, Region (II) constant and very discrete at intermediate purge flow rates, and Region (III) high and noisy at high purge flow rates. Knowing the dominant frequency behavior in Figure 11, cell speed values are most accurate in Region (II). The others were derived from a very low amplitude dominant frequency and are overcome by noise, as well as indicating low cell strength.

The shift in dominant frequency noted in the dominant frequency plots and spectrograms manifests in Figure 15 as a step increase in \( N_s \) for both the increasing and decreasing transient cases. The event occurs within the same narrow \( \Phi_p/\Phi_{\text{ref}} \) range of about 0.65 to 0.8 repeatedly in both the increasing and decreasing purge flow rate data trials, always corresponding to an increase of one cell. These data imply that there is a purge flow threshold after which the instabilities in the cavity experience a spontaneous “cell generation event,” whereupon \( N_s \) is increased by one.

The data in Figure 15 also highlights a purge flow region in which many have reported an inflection point in the sealing effectiveness trend [11,14]. Several studies have connected the formation of instabilities in the rim seal cavity with this inflection point [17,19]. For example, Graikos et al. [19] theorizes that the low-pressure regions created by the instability cells causes a pressure gradient that draws MGP flow into the rim seal cavity. The identified increase in the cell count for the transient cases – at the same purge flow range where an inflection point occurs in the sealing effectiveness – further corroborates a change in the flow physics. If the inflection point is indeed caused by the low-pressure cells drawing hot MGP air into the cavity, this effect would likely be exacerbated by an additional instability cell and attenuated as additional purge flow rate stabilizes the region. The hypothesis is that the instability transitions from increasing in strength to decreasing in strength, which implies conditions transition from favorable, where formation of the instability is supported, to non-favorable, where the flow in the rim seal cavity is stabilizing. This critical region containing both the highest cell coherence and inflection point is accompanied by the cell generation event, which further supports the idea that the instability is undergoing a transition that is driven by the changing flow conditions in the wheelspace.

The separation of Figure 15 into three separate operating regimes is further supported by computational fluid dynamics (CFD) simulations [11,33], accompanied by corresponding illustrations of the flow structure behavior in Figure 16. The CFD results in Figure 16(a,b,c) were generated using the same methodology as a URANS CFD study by Robak et al. [33] which used a quarter wheel geometry and periodic boundary conditions. The solution was validated using experimental data from the START facility. It should be noted that while Figure 16(a,b,c) is a simulation conducted using test facility representative geometry, Figure 16(d,e,f) is an illustration using general geometry. The CFD solution is depicted in Figure 16(a,b,c) using a purge flow mass fraction contour to illustrate MGP ingestion and is overlaid with cavity streamline to further emphasize the flow structures.

Region I is defined at low purge flow rates in Figure 16(a,d), the entire rim seal cavity is flooded with hot MGP flow. For these conditions, the purge flow rate is too low to seal the rim seal region, and the purge flow instead exits the under-platform region through leakage paths [33]. Figure 16(a,d) also shows that interaction between the MGP and purge flows in Region I occurs radially inboard from the rim seal location. Moreover, there are

![Figure 15. Cell count, its correlation with effectiveness and designation of regions I, II, and III.](Image 36x109 to 279x275)

![Figure 16. Purge flow mass fraction with overlaid cavity streamlines in (a) Region I, (b) Region II, and (c) Region III with accompanying illustrations using general geometry (d,e,f).](Image 326x122 to 579x290)
At the opposite end of the transient test, Figure 16(c,f) depicts Region III, defined by high purge flow rates where the cavity is mostly purged of MGP flow and shear interactions are occurring on the main gas path side outboard of the rim seal. The lack of cell formation within the rim seal is also supported by the low amplitude dominant frequency region at $\Phi_p/\Phi_{ref} > 1.1$ in Figure 10. While this operation range would ensure that the disk cavity is kept cool and free of MGP flow, it is also inefficient. The high purge flow rate leads to parasitic losses due to excessive flow bled from the MGP.

In the middle, Region II is defined by the formation of a discrete, vortical instability in the rim seal cavity at intermediate purge flow rates. Figure 16(b,e) specifically visualizes how the MGP flow is drawn into the wheel space. This behavior occurs in the region characterized by the stable dominant frequency for $0.4 < \Phi_p/\Phi_{ref} < 1.1$ in Figure 10, at the center of which the cell generation event occurs. Region II also coincides with the high amplitude region of Figure 11(a) meaning the high SNR of the fast-response signals and the resulting clear dominant frequency is indicative of high instability cell coherence.

The cell properties from the transient wheel speed trials are depicted in Figure 17. The cell speed shows a slight decreasing trend with increasing wheel speed, but the cell count, $N_s$, remains constant, apparently contradicting studies that have shown that ingestion can be induced by rotational effects [24]. It was noted in the discussion about Figure 13(b) and Figure 13(d) that the dominant frequency as a function of wheel speed had a slight decreasing trend. In Equation (7), the division of decreasing dominant frequency by decreasing cell speed causes the resulting constant cell count. While the constant cell count trend may be interpreted to suggest that flow instabilities are not functions of wheel speed, it is possible that the shear interaction between purge and MGP flow dominates over the rotational effects. Any transient shear effects due to change in relative velocity in the mid stage region due to change in wheel speed must also therefore be negligible.

The purge flow rate of the transient wheel speed trials lies within Region II, where the instability cells are at their maximum coherence. The magnitudes of both of the cell properties in Figure 17 are consistent with Region II in Figure 14 and Figure 15, respectively, from the transient purge flow rate trials. This supports the claim that purge flow rate in Region II has a greater impact than wheel speed on cell properties. Further studies are required to determine if rotational effects are still negligible with respect to shear effects in other purge flow regimes.

**CONCLUSIONS**

This study leverages the unique capabilities of the continuous-duration test article at the START lab to examine the effects of transient purge flow rate and wheel speed on the flow structures in the rim seal cavity of a single stage turbine. The measurements were collected using fast-response pressure and temperature sensors to examine time-resolved events. Flow behaviors identified in the measurements were further supported by visualization from CFD simulations.

A frequency analysis was conducted on a revolution-by-revolution basis, which reveals trends as functions of a transient independent variables. Through the use of a spectrogram-style plot, unique transient phenomena were identified at the frequency of the under-platform instability behavior. Namely, a shift in the dominant frequency was observed repeatably during the transient purge flow rate trials. Conversely, this analysis method indicated that the frequency of these flow instabilities is constant with respect to wheel speed, implying shear effects from the interaction between purge and main gas path flow dominate over rotational effects from the wheel speed at intermediate purge flow rates.

Significant hysteresis between the increasing and decreasing trials was present in the fast response temperature measurements for the transient purge flow rate dataset but not the transient wheel speed dataset. This discrepancy shows that the hysteresis was induced by thermal lag between the system hardware and the cooling purge flow. Similar behaviors were not present during the transient wheel speed trials, where the system was thermally soaked throughout the entire test campaign.

Finally, the flow instabilities in the rim seal cavity were characterized by determining the cell speed and count from the
dominant frequency and cross correlations of multiple pressure signals. Through this analysis, the identified shift in the dominant frequency of the transient purge flow rate was connected to an increase of one instability cell, typically occurring over the range of 20-30 revolutions. The identified change in \( N_b \) was also associated with a known inflection point in the rim sealing effectiveness as a function of purge flow rate, indicating that the sudden generation of a low-pressure flow instability draws MGP air into the wheel space.

The results of this study serve to expand upon all previous research endeavors into the topic of under-platform flow instabilities and to explore the behaviors of instabilities during transient processes. These observations will benefit future engine designers in improving engine efficiency and hot section component lifespan by understanding the types of flow phenomena that may be caused by transient operation.

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