VORTEX SHEDDING FROM STRUTS IN AN ANNULAR EXHAUST DIFFUSER

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ABSTRACT

Results from scale-model experiments and industrial gas turbine tests show that strut vortex shedding in an annular exhaust diffuser can effectively be modified by adding tapered chord to the struts. The struts are bluff bodies at full-speed, no-load conditions, when inlet swirl is close to 60°. Data from wind tunnel tests show that wake Strouhal number is 0.47, larger than that expected for an isolated cylinder wake. This value of Strouhal number agrees with those measured in full-scale exhaust diffusers. Wind tunnel tests showed that a strut with tapered chord most effectively reduced wake amplitudes and shifted shedding frequency. The tapered strut was also effective in reducing shedding amplitude in a scale-model diffuser. Finally, gas turbine tests employing a tapered strut showed significant reductions in unsteady pressure and noise. A major benefit of strut taper is a reduction of noise by uncoupling of vortex shedding from acoustic resonant response.

NOMENCLATURE

- $A_{max}$: maximum spectral amplitude among transducers
- $M$: Mach number = $u_a/c$
- $Re$: strut Reynolds number ($u_a c/v$)
- $St$: wake Strouhal number ($c/u_a$)
- $c$: strut chord (minimum chord for tapered struts)
- $f$: frequency of peak spectral amplitude
- $u_a$: radially-averaged total velocity at strut leading edge plane
- $\alpha$: nominal swirl angle at diffuser inlet plane

INTRODUCTION

A typical exhaust diffuser of an industrial gas turbine is annular with structural members, called struts, in the flow path. The struts extend radially from the inner to the outer annulus wall. Struts are optimized for base load operation, where flow from the turbine into the exhaust diffuser is axial or nearly so. By orienting the struts axially, incidence angle to the oncoming flow is small at base load. However, at full-speed, no-load (FSNL) conditions swirl exiting the last turbine blade-row can be large, up to 60° relative to axial. At high incidence angles the struts act as bluff bodies and consequently cause unsteady wakes.

GE gas turbine tests of exhaust diffusers have shown relatively higher levels of unsteady pressure and noise at FSNL operating points than at base load. Data show that unsteady pressure amplitudes of up to 2 psi (peak-to-peak) can occur. Typically the highest unsteady pressures are measured near the struts, with amplitudes decreasing both upstream and downstream of them. Unsteady pressure spectra show a dominant frequency. The sharpness of spectral peaks and acoustic data from FSNL tests suggest that an acoustic resonance of the diffuser flow path is excited. One possible acoustic stimulus is vortex shedding from struts when the swirl angle is large. It is conjectured that unsteady pressures are highest when vortex shedding frequency couples with an acoustic frequency of the flow path.

Excitation of acoustic modes by vortex shedding are not uncommon phenomena. Parker and Stoneman (1989) review occurrences of vortex shedding excitation of acoustic oscillations in internal flow systems with flat plates. The acoustic mode excited is a function of the characteristic vortex shedding Strouhal frequency. For flow aligned with the flat plates, the acoustic response can be affected by subtleties of the plate geometry such as leading and trailing-edge shape. Parker and Stoneman also recognize that vortex shedding characteristics, such as frequency, can be altered by acoustic response. The pressure amplitudes created when an acoustic resonance is excited are significantly larger than those from vortex shedding alone. An example of severe damage that can occur from acoustic resonances in diffusers is described by Rizk and Seymour (1964).

In order to understand and reduce diffuser dynamics encountered at FSNL conditions, a test program was initiated. The program involved three test phases - the first two with scale models and the third with full-size gas turbines.
third with a full-scale gas turbine. Since strut vortex shedding was considered as a possible stimulus, the first test was designed to observe and measure vortex shedding from a baseline strut and to allow for screening of modified struts to change vortex shedding. In order to quickly screen new struts, the first phase of experiments was performed in a 3-strut, "component" two-dimensional wind tunnel, with strut aspect ratio and mid-span pitch scaled from the annular diffuser. Three struts were considered to provide sufficient interaction effects, with the central strut's wake being most representative. The second phase of testing was performed in a scale-model annular exhaust diffuser. Tests in an annular model allowed for verification of strut vortex shedding performance in a three-dimensional geometry. The first two phases of testing were laboratory experiments designed to study strut vortex shedding. Since gas turbine Mach numbers were not matched, resonance between vortex shedding and acoustics could not be investigated. The third test phase, gas turbine tests at FSNL conditions, was run in order to measure the effects of strut design in an environment with correct acoustics.

New strut designs screened in the 3-strut component tests were chosen based on their probability of modifying wake shedding and on their ease of implementation into exhaust diffuser hardware. Strut designs that had a potential to change dominant wake frequencies or significantly reduce the amplitude of wake fluctuations, or ideally both, were considered. Manipulation of bluff-body vortex shedding has been studied extensively. One class of techniques often employed involves the addition of plates near the bluff body. As examples, splitter plates in the near wakes of circular cylinders affect wake frequencies and drag (Roshko, 1955), a spoiler plate attached to one side of an airfoil affects predominant shedding frequencies (McLachlan and Karamcheti, 1985), and the addition of a tandem bluff body either upstream or downstream from the original can influence the collective vortex shedding and drag (Lesage and Gartshore, 1987). Although these techniques are effective methods to reduce wake dynamics and drag, they are typically useful only over a small angle-of-attack range. An essential requirement for a strut modification is that it is effective over a large range of swirl angles (0° through 60°). A new design should not improve dynamics at FSNL at the expense of reduced performance at base load operation. Cimbala & Garg (1991) tested a splitter plate placed at the trailing side of a cylinder with the additional feature that the splitter plate is hinged, allowing it to float as dictated by the flow. Although such a floating splitter may be effective over a wider range of swirl, implementation of a hinged splitter in an annular geometry, particularly in a high temperature environment, may be difficult. The above-listed techniques generally require that additional objects be introduced, adding complexity to the mechanical design of the flow path.

Another class of techniques to control wakes is the addition of vortex generators. Vortex generators effectively keep flow attached, but only up to moderate angles of attack. Larger-scale vortex generators which introduce streamwise vorticity and break-up dominant spanwise structure can be effective in reducing vortex shedding amplitudes but are not necessarily effective in changing shedding frequency (Gulati, 1990). Higuchi and Takahashi (1989) studied the aerodynamic characteristics of vented bluff bodies. Their results showed that vents, in the form of slots in the bluff body, can change vortex shedding strength and drag. The vents act as wake fillers, and alter the communication between separations from each edge of the bluff body.

For the tests reported on here, quantitative data is presented in the form of amplitude spectra from unsteady pressure transducers in the vicinity of struts. Peak frequencies are nondimensionalized as Strouhal number, St based on strut chord and total velocity. Data from FSNL gas turbine tests show that resonance occurred at St = 0.47 at swirl angles near 60°. The 3-strut component and scale-model annular tests produced vortex shedding at St = 0.47 and 0.38, respectively. These St values are sufficiently close to real machine values at resonant conditions to suggest that vortex shedding is a component of exhaust diffuser dynamics.

Five strut concepts were screened in the 3-strut component wind tunnel. The five concepts are called baseline, vortex generator, tapered chord, long chord, and vented. The vortex generator, tapered chord, and long chord designs are relatively simple modifications to the existing struts. The vented design involves a more significant modification since air paths through the struts are required. Each of the four new strut designs showed some improvement in wake dynamics. However, the tapered chord clearly performed the best; it significantly shifted wake frequency and reduced peak vortex shedding amplitudes. Since the tapered strut performed best in the screening tests, this design was tested in the annular scale-model test. The tapered strut was again effective in reducing peak vortex shedding amplitude and shifting frequency. Tapered struts were then installed in a full-scale exhaust diffuser. Gas turbine tests with the tapered strut showed significant unsteady pressure amplitude and noise level reductions, relative to the baseline design.

**TEST SETUPS: PHASES 1, 2 AND 3**

**(1) 3-Strut Component Wind Tunnel**

The test section of the 3-strut component wind tunnel is shown in Fig. 1. Three unstaggered struts were mounted in the test section. The baseline struts were 1/6 scale of gas turbine size with a chord of 12.4 cm (4.9 in.) and a spacing of 15.7 cm (6.2 in.), equivalent to the mid-span radial struts' pitch. The rectangular test section, 122 cm (48 in.) in length, 82.3 cm (32.4 in.) in height and 14.6 cm (5.75 in.) in...
width, was supplied by a rectangular nozzle from a 122 cm (48 in.) diameter plenum. The three struts were mounted on a rotatable disk, which was centered on the rear side wall. "Swirl" could be varied by rotating the disk to the desired angle. Although the tests focused on the \( \alpha = 60^\circ \) case, lower swirl angles of 45\(^\circ\), 30\(^\circ\), and 0\(^\circ\) were also looked at. Unsteady pressure data were obtained at sixteen locations on the disk, and these are shown in Fig. 1. Unsteady pressure transducers (PCB model 103A02) were mounted on the sixteen pressure taps. Test section velocity \( u_{in} \) was 30.5 m/s (100 ft/s), and the velocity at the inlet was spatially uniform to within \( \pm 1.25\% \). Test section frequency spectra were flat with no discernible peaks, when no struts were installed.

Unsteady pressure data were acquired with a 486 personal computer. Signals from each transducer were filtered and amplified (gain = 10) by a Krohn-Hite model 3944 multichannel filter. Transducer signals were low-pass filtered at 500 Hz, sampling rate was 1500 Hz, and sampling time was 2 sec. Data are presented in the form of amplitude spectra of the unsteady pressure signal. In order to smooth spectral fluctuations, each 3000 point sample was partitioned into ten 512 point rectangular windows with overlap. Each spectrum shown is an ensemble average of the ten 512 point FFTs. Smoothing in this manner allowed for improved spectral peak determination at the expense of frequency resolution. The spectral amplitudes shown are in arbitrary units on a linear scale.

Five strut designs, shown in Fig. 2, were screened. The following describes the five designs in detail.

**Baseline.** The baseline strut is a 1/6-scale model of the exhaust diffuser strut. The strut profile is a NACA 16 with a maximum thickness of 2.6 cm (1.0 in.) and a chord \( c \) of 12.4 cm (4.9 in.).

**Vortex generators.** Four vortex generator tabs are mounted on the pressure side of the baseline strut near its trailing edge (Fig. 2b). The vortex generators are oriented at 20\(^\circ\) relative to the axial direction. The tabs' axial lengths are 3.73 cm (1.47 in.), and their height at the strut trailing-edge is 1.15 cm (.45 in.).

**Tapered.** To test the effects of varying a characteristic length scale, a tapered strut, with variable chord along its span, was tested. Based on initial promising tests, several variations of the tapered strut were tested. The tapered strut shown in Fig. 2c is identified as "tapered-1.5". "Tapered" indicates that the strut chord (and thickness) varies linearly along its span. The strut profile remains the same at all cross sections. "1.5" indicates the amount of chord taper - the chord at one end is always fixed at 1X (12.4 cm, 4.9 in.), and the chord at the other end of the strut is 1.5X (18.6 cm, 7.35 in.). Smaller amounts of taper, 1.38 and 1.25, were also tested. In each case taper was added to the strut trailing-edge.

**Long chord.** The long chord design also uses a NACA 16 strut profile, with a chord 1.5X larger (18.6 cm, 7.35 in.) than the baseline. The long chord effectively increases the solidity of the flow path at high swirl angles. The long chord was tested to help distinguish between the solidity and nonuniform chord effects of the tapered strut.

**Vented.** The baseline vented strut has three rows of holes, each row with seven .95 cm (.38 in.) holes. The holes are angled at 45\(^\circ\) relative to the chord line, such that at \( \alpha = 45^\circ \) the holes are in line with the flow direction.
(2) 1/6-scale Annular Exhaust Diffuser Model

The 1/6-scale model of the annular exhaust diffuser is shown in Fig. 3. The diffuser outer wall expansion (half) angle is approximately 6°, and the centerbody is of uniform diameter. Ten equally spaced radial struts of chord 12.4 cm (4.9 in.) are located one chord length from the diffuser inlet plane. Inlet swirl is provided by a radial swirler. Inlet total velocity \( u_\infty \) was 43.9 m/s (144 ft/s) with a radial variation of ±4.6 m/s (15 ft/s). Nominally \( \alpha = 60° \), but \( \alpha \) dips to 50° near the centerbody. Unsteady pressure instrumentation and the data acquisition system were like those used in the 3-strut component tests. Pressure transducers (locations B1 through B7 and C1 through C5 only) were mounted on the diffuser outer wall at equivalent positions relative to a selected strut as those shown in Fig. 1.

Two strut designs, the baseline and tapered chord, were tested. The tapered chord strut was selected from the screening tests to be the most effective in vortex shedding amplitude reduction and frequency shift. Two variations of a tapered strut were investigated. The first had 1.5 taper at the strut trailing-edge. The second design tested was one with 1.65 overall taper, consisting of 1.4 trailing-edge taper and 1.25 leading-edge taper. In both cases maximum chord was mounted at the root.

(3) Full-scale Gas Turbine

Full-scale tests at full-speed, no-load (FSNL) gas turbine conditions were run in order to compare the performance of the tapered strut with that of the baseline design. The tapered design tested was the tapered-1.65, which performed best in annular scale-model tests. Inlet guide vane (IGV) settings were changed in order to measure exhaust diffuser dynamics under varying mass flow rate and exhaust temperatures, anticipating that exhaust temperature would affect diffuser acoustics. Instrumentation included eighteen transducers on the outer wall of the exhaust diffuser. Six transducers were circumferentially-located one-half chord length aft of the diffuser inlet plane. The remaining transducers were positioned in the vicinity of a selected strut. The flow conditions for the gas turbine exhaust diffuser at FSNL are compared with those for the laboratory tests in Table 1.

Table 1: Comparison of flow conditions among tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \alpha )</th>
<th>( M )</th>
<th>( Re )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-scale gas turbine (FSNL)</td>
<td>60°</td>
<td>.45</td>
<td>3,000,000</td>
</tr>
<tr>
<td>1/6-scale annular model</td>
<td>60°</td>
<td>.11</td>
<td>400,000</td>
</tr>
<tr>
<td>3-strut component</td>
<td>60°</td>
<td>.09</td>
<td>300,000</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

(1) 3-Strut Component Wind Tunnel

Figure 4 shows smoke-wire flow visualization of the baseline strut wake at \( \alpha = 60° \). The wakes contain vortical structure, seen most clearly at the center strut's trailing edge. Flow separates from the leading and trailing edges, and the wake of a strut strongly interacts with the adjacent strut. Visualization for \( \alpha = 45° \) is similar to that shown here. At \( \alpha = 30° \) interactions between wakes and struts are weaker, and at \( \alpha = 0° \) small isolated wakes exist, but flow remains attached over most of each strut.

Figure 5 shows amplitude spectra for the five strut designs at \( \alpha = 60° \). The spectra shown are for those transducer locations which resulted in maximum peak amplitude for each design. Maximum amplitudes \( A_{\text{max}} \) for the baseline and vortex generators designs are 15.1 and 10.5, respectively. Peak frequencies are similar for both designs, as indicated by \( St \) values of 0.47 and 0.50, respectively. Table 2 shows \( A_{\text{max}} \), transducer location corresponding to \( A_{\text{max}} \), and \( St \) for five designs and three \( \alpha \). The long chord and vented struts shifted the dominant frequency higher, to \( St = 0.57 \) in both cases. Peak amplitudes are 10.9 and 14.7 for the long chord and vented designs, respectively. The tapered-1.5 design shifted the dominant frequency even higher to \( St = 0.67 \) and reduced the peak amplitude.
Table 2: $A_{max}$, transducer location corresponding to $A_{max}$, and $St$, $\alpha = 60$, 45, and 30°. $u_{ref} = 30.5$ m/s (100 ft/s).

<table>
<thead>
<tr>
<th>STRUT DESIGN</th>
<th>$A_{max}$ (location)</th>
<th>$St$</th>
<th>$A_{max}$ (location)</th>
<th>$St$</th>
<th>$A_{max}$ (location)</th>
<th>$St$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>15.1 (C5)</td>
<td>.47</td>
<td>13.4 (C5)</td>
<td>.47</td>
<td>4.06 (C5)</td>
<td>.68</td>
</tr>
<tr>
<td>Vortex generators</td>
<td>10.5 (C3)</td>
<td>.50</td>
<td>7.75 (C3)</td>
<td>.50</td>
<td>2.35 (B2)</td>
<td>.67</td>
</tr>
<tr>
<td>Tapered-1.5</td>
<td>6.71 (C2)</td>
<td>.57</td>
<td>4.31 (B4)</td>
<td>.52</td>
<td>no discrete peaks</td>
<td>—</td>
</tr>
<tr>
<td>Long chord</td>
<td>10.9 (C2)</td>
<td>.57</td>
<td>9.07 (B2)</td>
<td>.56</td>
<td>no discrete peaks</td>
<td>—</td>
</tr>
<tr>
<td>Vented</td>
<td>14.7 (C5)</td>
<td>.57</td>
<td>no discrete peaks</td>
<td>—</td>
<td>did not test</td>
<td>—</td>
</tr>
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</table>

Figure 6: Sample pressure vs. time traces comparing baseline and tapered-1.5 designs. $\alpha = 45^\circ$.

Figure 7: Smoke-wire flow visualization of tapered-1.5 strut at $\alpha = 45^\circ$.

Values of $St$ measured here are considerably larger than those expected for isolated airfoils at high incidence angles or for classical cylinder wakes. Data for isolated airfoils at $\alpha = 60^\circ$ show values of $St$ to be in the range of 0.17 to 0.24 (Fung, 1955). Data from the 3-strut component tests show that baseline $St = 0.47$. To check consistency between our tests and those presented by Fung, the test section was modified so that only the central strut was installed. Peak amplitude in the wake of an isolated baseline strut occurred at $St = 0.25$, close to the values of Fung. However, wake frequencies measured by Cenedese, et al. (1981) for a single airfoil at $\alpha = 60^\circ$ yielded $St = 0.46$, a value close to that measured in the 3-strut test. An important aspect of the setup of Cenedese, et al. is that although they studied an isolated airfoil, the wind tunnel test section height was only about twize the airfoil chord. At high incidence angles blockage due to the airfoil was therefore large.

One possible explanation to resolve such discrepancies in $St$ is that closely spaced struts redistribute wake structure so that transducers detect vortices shed from both edges of each strut, creating an apparent frequency doubling. Similarly a transducer located in the central portion of a circular cylinder wake records vortices shed from both sides. However, the reason for the high values of $St$ may be more fundamental. Flow visualization such as that shown in Fig. 4 reveals "jets" at the strut trailing edge, from the pressure side. As flow accelerates in the narrowing passage between the leading-edge separation streamline and the pressure side of the "downstream" strut, a locally higher velocity is created where separation from the strut trailing-edge occurs. The locally higher velocity at the trailing edge would likely result in higher wake frequencies and therefore high values of Strouhal number that are based on incoming freestream velocity. A similar argument could be made for the geometry studied by Cenedese, et al. where wind tunnel blockage would create locally higher velocities at the separation lines.

Figure 6 shows sample pressure vs. time traces comparing the baseline and tapered struts. The time trace for the baseline case clearly shows a strong periodic fluctuation which matches the 115 Hz peak of its spectrum (Fig. 5). The time trace for the tapered-1.5 design shows a significantly reduced fluctuating component. Figure 7 shows a sample flow visualization of the tapered-strut wake. Although the visual differences between the wakes are more subtle than differences between spectra, less large-scale vortical structure appears in the tapered-strut wakes than in the baseline wakes.

Data for the five strut designs at $\alpha = 45^\circ$ and 30° are shown in Table 2. Three observations are noteworthy. First, the tapered-1.5 strut reduced peak amplitude from 13.4 to 4.31 and shifted peak $St$ from .47 to .52 at $\alpha = 45^\circ$. Second, amplitudes are comparable at $\alpha = 30^\circ$. Significantly, the greatest reduction in peak amplitude and frequency shift was obtained by the tapered strut. Tapered strut results with varying amounts of taper will be discussed later. Data from all transducers uniformly indicate that the tapered strut performed best.

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Figure 8: Amplitude spectra comparing tapered struts with baseline strut. $\alpha = 60^\circ$. Location is C5.

$60^\circ$ and $45^\circ$ but drop off considerably at $\alpha = 30^\circ$. Third, the vented strut did extremely well at $\alpha = 45^\circ$, where no discrete peak was found. Recalling that the vented strut did not reduce peak amplitudes at $\alpha = 60^\circ$, it appears that the success of the vented design is highly dependent on the relative angle between in the incident flow and holes comprising the vents.

Additional Tapered Strut Results. Data from the 3-strut component tests indicate that the tapered-1.5 strut is overall most effective in reducing unsteady pressure amplitudes and in shifting wake frequencies. Varying strut chord along its span was motivated by the fact that the characteristic wake frequency of a bluff body scales with its diameter or, equivalently in this case, with its chord. This information is implicit in the definition of Strouhal number; frequency is inversely proportional to length scale. By varying the characteristic length scale along the strut's span, wake formation is disrupted since a single dominant frequency is not apparent anymore. The flow doesn't have a single length scale by which to set its frequency. Earlier it was conjectured that the higher than expected wake frequencies were perhaps caused by flow acceleration in between struts. If this is the case, the appropriate length scale which sets wake frequencies may in fact be the effective gap distance in between struts. It follows then that tapering has a similar disruptive effect since the distance between struts also varies in the spanwise direction.

Further tests were conducted in order to investigate the effect of amount of taper on amplitude reduction and frequency shift. Trailling-edge tapers of 1.25 and 1.38 were investigated. Figure 8 shows amplitude spectra for various amounts of taper. Amplitude decreases with increasing trailing-edge taper. The results show that amplitudes decrease from 15.1 to 9.37, 6.91 and 6.71 as trailing-edge taper is increased by amounts of 1.25, 1.38 and 1.5, respectively. Also, peak amplitudes shift to higher frequencies as the amount of taper increases. Although the amplitude reduction realized with different tapers varied somewhat with transducer location, the shift of peak frequency with increasing taper was consistently observed at all transducers.

Perhaps the best measure of taper effectiveness is to compare $A_{\max}$ for each taper design at $\alpha = 60$ and $45^\circ$. This comparison is shown in Table 3. Percent reductions in $A_{\max}$ relative to baseline, peak frequency $f$, and percent increases in $f$ are also indicated in Table 3. The data show that taper was also effective at $\alpha = 45^\circ$. Each amount of taper, even 1.25, essentially eliminated vortex shedding peaks. The data suggest, therefore, that the effectiveness of taper is higher for $\alpha = 45^\circ$ than for $\alpha = 60^\circ$; the amount of taper required to reduce vortex shedding amplitude by a prescribed amount is less than that required for $\alpha = 60^\circ$.

Table 3: Effectiveness of trailing-edge taper on maximum amplitudes and frequencies. $\alpha = 60$ and $45^\circ$.

<table>
<thead>
<tr>
<th>Design</th>
<th>$A_{\max}$ (location)</th>
<th>$\Delta A_{\max}$ %</th>
<th>$f$ (Hz)</th>
<th>$\Delta f$ %</th>
<th>$A_{\max}$ (location)</th>
<th>$\Delta A_{\max}$ %</th>
<th>$f$ (Hz)</th>
<th>$\Delta f$ %</th>
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<tr>
<td>1.00</td>
<td>15.1 (C5)</td>
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<td>-13.6 (C5)</td>
<td>-111</td>
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<tr>
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<td>4.31 (B4)</td>
<td>-68</td>
<td>132</td>
<td>+19</td>
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Figure 9: Spectra comparing tapered struts with baseline in 1/6-scale annular exhaust diffuser. Location is B3.

Table 3: Effectiveness of trailing-edge taper on maximum amplitudes and frequencies. $\alpha = 60$ and $45^\circ$.

(2) 1/6-scale Annular Exhaust Diffuser Model

Figure 9 shows amplitude spectra for the baseline strut and two versions of the tapered strut as tested in the 1/6-scale annular model. Spectra shown correspond to the location for which maximum amplitude for the baseline strut was recorded. The spectral peak for the baseline strut is now relatively broader than that for the 3-component tests. $S_t = .38$, somewhat lower than that measured in the 3-strut tests. This difference may be attributed to three-dimensional effects such as nonuniform inlet velocity and swirl profiles, a diffusing endwall, and varying strut pitch.

The tapered-1.5 strut produced an amplitude reduction of 1.43 to
Figure 10: FSNL gas turbine exhaust diffuser spectra. (a) Baseline strut, (b) Tapered-1.65 strut.

Figure 11: FSNL exhaust diffuser unsteady pressure amplitudes with varying IGV setting.

The amplitude spectra for inlet guide vane (IGV) settings of 54 and 74. These spectra are for those transducer locations which resulted in maximum peak amplitude for each IGV setting. The characteristic behavior of the baseline exhaust diffuser is that unsteady pressure amplitudes and noise increase as IGVs are opened from 54 to 84 at FSNL. For example, two low amplitude peaks at $f = 134$ Hz. and $157$ Hz. become one high amplitude peak at $f = 127$ Hz. for the higher IGV setting (Fig. 10a). Figure 11 clearly shows the trend of increasing dynamics with opening IGV setting.

That unsteady pressure signals increased rapidly and appeared to lock into a preferred frequency suggest that an acoustic resonance was excited. At no load and constant rotor speed, as the IGVs are opened, mass flow through the diffuser increases and temperature decreases. The effects of this are two-fold; changes in velocity affect vortex shedding frequency and a decrease in temperature affects acoustic frequency. Shifting of these values could collectively act to enhance coupling of vortex shedding and acoustics, creating a resonance. The six circumferentially-positioned pressure transducers located forward of the struts allowed for determining the mode shape of resonance for baseline struts. The relative phases among signals from these transducers are plotted in Fig. 12a. The linear fit to these phases, showing $1080^\circ$ (3 x 360°) accumulated phase around the circumference of the diffuser, suggests that the acoustic wave is a nodal diameter $n = 3$ circumferentially-traveling (spinning) wave. That an $n = 3$ wave is a traveling wave is consistent with the observations of Parker and Pryce (1974), who found that for annular passages traveling waves are common when the number of half waves is not equal to the number of struts. The approximately uniform amplitude among these transducers is also consistent with a spinning...
diffuser. Given that a spinning tapered struts is to shift vortex shedding frequency and reduce its acoustic resonance. In fact, if the tapered struts are altered by tapering the struts, then a decoupling of excitation from the resonance in the baseline case and if vortex shedding was sufficiently amplitudes. If vortex shedding is the excitation source for the acoustic wave and the consistency of Strouhal numbers among the experiments. The scale-model annular diffuser tests suggested that a strut with combined leading and trailing-edge taper, with a net chord taper of 65%, is most effective in the annular geometry. Therefore this dual taper design was chosen for gas turbine testing.

Full-scale tests at full-speed, no-load conditions employing a tapered strut with combined leading and trailing-edge taper resulted in approximately factors of three reductions in unsteady pressure amplitudes. Baseline strut tests at FSNL conditions showed that a spinning wave exists in the exhaust diffuser. The presence of an acoustic wave and the consistency of Strouhal numbers among the laboratory and gas turbine tests indicate that a coupling between vortex shedding and acoustics exists for a diffuser with baseline struts. The results suggest tapered struts decouple vortex shedding excitation and acoustic response of the diffuser.

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SUMMARY

Scale-model tests and a full-scale gas turbine test were used to diagnose and reduce relatively high levels of unsteady pressures in an industrial gas turbine exhaust diffuser operating at full-speed, no-load conditions. Past experience suggested that the source of high dynamics may have been radial struts near the forward portion of the annular diffuser. Since swirl can be as high as 60° at FSNL operation, efforts were first focused on vortex shedding from the axially-oriented struts. Wind tunnel tests established a vortex shedding Strouhal number of 0.47, based on strut chord and total velocity. This Strouhal value matched that measured in a full-scale diffuser operating at FSNL.

Figure 12: FSNL baseline diffuser acoustic signature. Data were obtained from 6 transducers forward of struts. (a) phase, (b) amplitude.
during the gas turbine tests is appreciated. Data reduction by Ralph Bush is recognized. The work benefited greatly from insights into the acoustics of the problem provided by Rich Loud (Schenectady), Bob Hedeen, Graham Holmes, Z. Hu, Ramani Mani (CR&D), and Joe Alford (GE Aircraft Engines). The contribution of Chris Wilkes to the 3-component tests is also recognized.

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