ACCURATE PREDICTIONS OF UNSTEADY FORCING ON TURBINE BLADES ARE ESSENTIAL FOR THE AVOIDANCE OF HIGH-CYCLE-FATIGUE ISSUES DURING TURBINE ENGINE DEVELOPMENT. FURTHER, IF ONE CAN DEMONSTRATE THAT PREDICTIONS OF UNSTEADY INTERACTION IN A TURBINE ARE ACCURATE, THEN IT BECOMES POSSIBLE TO ANTICIPATE RESONANT-STRESS PROBLEMS AND MITIGATE THEM THROUGH AERODYNAMIC DESIGN CHANGES DURING THE DEVELOPMENT CYCLE. A SUCCESSFUL REDUCTION IN UNSTEADY FORCING FOR A TRANSONIC TURBINE WITH SIGNIFICANT SHOCK INTERACTIONS DUE TO DOWNSTREAM COMPONENTS IS PRESENTED HERE. A PAIR OF METHODS TO REDUCE THE UNSTEADINESS WAS CONSIDERED AND RIGOROUSLY ANALYZED USING A THREE-DIMENSIONAL, TIME RESOLVED REYNOLDS-AVERAGED NAVIER STOKES (RANS) SOLVER. THE FIRST METHOD RELIED ON THE PHYSICS OF SHOCK REFLECTIONS ITSELF AND INVOLVED ALTERING THE STACKING OF DOWNSTREAM COMPONENTS TO ACHIEVE A BOWED AIRFOIL. THE SECOND METHOD CONSIDERED WAS CIRCUMFERENTIALLY-ASYMMETRIC VANE SPACING WHICH IS WELL KNOWN TO SPREAD THE UNSTEADINESS DUE TO VANE-BLADE INTERACTION OVER A RANGE OF FREQUENCIES. BOTH METHODS OF FORCING REDUCTION WERE ANALYZED SEPARATELY AND PREDICTED TO REDUCE UNSTEADY PRESSURES ON THE BLADE AS INTENDED. THEN, BOTH DESIGN CHANGES WERE IMPLEMENTED TOGETHER IN A TRANSONIC TURBINE EXPERIMENT AND SUCCESSFULLY SHOWN TO MANIPULATE THE BLADE UNSTEADINESS IN KEEPING WITH THE DESIGN-LEVEL PREDICTIONS. THIS DEMONSTRATION WAS ACCOMPLISHED THROUGH COMPARISONS OF MEASURED TIME-RESOLVED PRESSURES ON THE TURBINE BLADE TO OTHERS OBTAINED IN A BASELINE EXPERIMENT THAT INCLUDED NEITHER ASYMMETRIC SPACING NOR BOWING OF THE DOWNSTREAM VANE. THE MEASURED DATA WERE FURTHER COMPARED TO RIGOROUS POST-TEST SIMULATIONS OF THE COMPLETE TURBINE ANNULUS INCLUDING A BOWED DOWNSTREAM VANE OF NON-UNIFORM PITCH.

INTRODUCTION

NOWADAYS A CONSIDERATION OF UNSTEADY AERODYNAMICS IN TURBINE COMPONENTS IS AN INTEGRAL PART OF THE DESIGN PROCESS IN INDUSTRY [1]. AS A CONSEQUENCE, SEVERAL REVIEWS ON THE TOPIC AND ITS DEVELOPMENT AS AN EFFECTIVE DESIGN TOOL ARE AVAILABLE IN THE OPEN LITERATURE (SEE, E.G. [2-5]). OFTEN DESIGNERS ENCOUNTER RESONANT-STRESS PROBLEMS DURING ENGINE DEVELOPMENT, AND THESE ARE TYPICALLY ADDRESSED THROUGH CAREFUL CONSIDERATION OF THE BLADE CAMPBELL DIAGRAM THAT PLOTS NATURAL FREQUENCIES OF VIBRATORY MODES AS WELL AS EXPECTED SOURCES OF UNSTEADINESS ARISING FROM KNOWN AIRFOIL COUNT VS WHEEL SPEED. THIS PROCESS IS TERMED “RESONANT AVOIDANCE” [6] BY GREITZER AND HIS CO-WORKERS. HOWEVER, THE COMPROMISES THAT DESIGNERS MAKE IN TERMS OF AIRFOIL COUNT TO KEEP AWAY FROM THE NATURAL FREQUENCIES OF TURBINE BLADES DURING NORMAL ENGINE OPERATION CAN LEAD TO INCREASED MODULE WEIGHT AND LIFE CYCLE COSTS. SO, IT IS PREFERABLE TO EMPLOY AERODYNAMIC DESIGN TECHNIQUES TO MITIGATE THE UNSTEADY INTERACTION THAT ARISES IN THE TURBINE SO THAT THE SEVERITY OF ANY RESONANCES THAT MIGHT OCCUR IS REDUCED.

row are reflected from the downstream stationary vane row, and these travel back upstream to cause additional shock/shock and shock/boundary layer interactions.

In a previous study [9] the measured unsteady interaction between the blade row and the downstream vane for a baseline turbine configuration was studied extensively and compared to rigorous post-test simulations using time-resolved Reynolds-Averaged Navier-Stokes (RANS) analysis. It was found that the physics of the shock interaction and the resulting unsteadiness on the blade in the region impacted by shock reflections from the downstream vane row was well predicted overall. One major finding from that effort was that the dominant interaction that occurs on the blade suction sides downstream of the throat is due to a pair of reflected shocks that were generated two- and three-passages removed from the impacted airfoil. That is the source of the dominant first-harmonic unsteadiness seen by other researchers [8]. Another finding was that at most measurement locations on the blade, the simulation was conservative. That is, the measured magnitude of the unsteady pressure was less than that predicted at the frequency associated with shock reflections. That study [9] was later extended to include the effects of as-manufactured blades on the reflected-shock unsteadiness [10]. Inclusion of as-manufactured geometries improved the quality of the results simulated numerically, and it also allowed a demonstration of unsteadiness reduction on a specific airfoil through careful arrangement of blades around the annulus.

Since the unsteady pressures in the baseline transonic turbine rig were qualitatively well predicted and the shock interaction physics well represented in simulations, it was deemed worthwhile to consider the effects of aerodynamic design changes on the unsteady pressures due to shock interactions in the stage. Accordingly, a series of proof-of-concept studies was conducted to that end [11]. A great number of possibilities was considered to decrease the unsteadiness on the blade suction side downstream of the throat. These included design changes to the blade itself (since it is ultimately the source of shocks in the flowfield) as well as changes to the downstream stationary component. In terms of the former, the blade shape was modified to reduce the circumferential pressure gradient across the rotating airfoil passage [1, 12] and to alter the character of the blade loading to push the peak suction location further aft [13]. In terms of the latter, four distinct types of design changes were assessed. These included changes in the downstream vane geometry relative to its stacking axis [1], aspiration from the airfoil pressure side [14], clocking of the airfoil relative to the upstream vane row [15, 16], and asymmetric vane spacing [17].

Overall, it was found that changes in the downstream vane were more efficacious for reducing the forcing on the blade, and this was likely due to the attention paid to producing a low-shock-loss blade in the initial design of the turbine [7]. So, modular turbine experimental components were produced to allow assessment of all four types of downstream vane changes on blade unsteadiness. In particular, alteration of the downstream vane stacking axis and asymmetric airfoil spacing were both predicted to reduce the blade unsteadiness markedly, and these were selected for the first assessment of the effect of the design changes in a rotating turbine experiment. Separate accountings of the effects of vane airfoil stacking variations and non-uniform pitch-wise spacing on blade suction side unsteadiness is given below along with results of experimental verification testing for a bowed, asymmetric vane configuration.

**NOMENCLATURE**

- DFT Discrete Fourier Transform
- E Engine Order = f / (N / 60)
- f frequency of unsteadiness, Hz
- N blade rotational speed, revolutions per minute
- Ptot inlet total pressure, kPa
- Δ percent difference in a variable, e.g. total pressure loss
- 1V Inlet guide vane, first vane
- 1B Stage one turbine blade, first blade
- 2V Second stage turbine inlet guide vane, second vane

**BASELINE TURBINE GEOMETRIC, ANALYSIS, AND EXPERIMENTAL DETAILS**

In this paper the effects of design changes to the downstream vane in a counter-rotating turbine on blade unsteadiness are compared to baseline turbine results obtained in an experiment described previously [9, 10]. In the experiments a high work, single-stage transonic turbine with an exit relative Mach number (ideal) of 1.45 at mid-span sits upstream of the vane. Because the downstream airfoil is consistent with the inlet-guide-vane of a counter-rotating Low
Pressure Turbine, it turns the flow very little (≈11°) in the absolute frame of reference. Again, considering Fig. 1, this sets up a shock reflection that returns to the blade suction side downstream of the throat.

To predict time-resolved loadings in this situation an unsteady RANS analysis was conducted with a commercially available turbomachinery solver [18]. The airfoil counts in the baseline turbine experiment were selected originally to allow for rigorous periodic-unsteady analysis with small computational cost. Specifically, the upstream vane, blade, and downstream vane counts were 23, 46, and 23, respectively. So, a rigorous periodic-unsteady calculation with symmetric vanes requires only a 1/2/1 computational model. In keeping with [9], great care was taken prior to final comparisons of simulated and experimental Fourier components to ensure convergence with respect to the grids used (1.8x10^6 nodes per vane passage, 0.83x10^6 nodes per blade), the time-step (200 steps/blade passage with 20 inner iterations for dual time stepping), and the periodicity of the solutions [19] prior to post-processing.

All experimental data were obtained in the full-scale, short-duration Turbine Research Facility at AFRL [20] and dynamical similarity was employed for simulations used for comparison to experiments. That is, all final computations were completed at matched speed parameter (353 rpm/K^1/2), stage-and-one-half total-to-static pressure ratio (5.13), ratio of specific heats (1.4), and first vane exit Reynolds number based on axial chord (1.56x10^6). Converged periodic unsteady predictions were compared to unsteady pressures measured with piezo-resistive pressure transducers accurate to 0.05% of full scale [9]. All measured pressures were also ensemble-averaged with respect to the rotational period of the turbine wheel over approximately 100 revolutions. Again, complete details on the experimental techniques and the investigations with the baseline turbine are found in [20] and [9, 10], respectively.

For all investigations of the effects of design changes on the predicted unsteadiness at the blade row, the same simulation practice was followed with two exceptions. First, a substantially smaller number of grid nodes was used for the vane (0.36x10^6) and blade passages (0.29x10^6). This was sufficient to guide design changes, as is seen below, and it was also a necessary compromise that enabled the completion of the design studies in a reasonable wall-clock time. Second, while both cooled and uncooled airfoils (i.e. rainbow cooling) were used in the upstream vane and blade rows for the experiments, cooling models are absent in this study. This is because it was found previously [9, 10] that the interaction between the shocks on the blade row and the uncooled downstream vane was found to be largely independent of the assumptions made with respect to cooling of the upstream vane and blade rows.

**EFFECTS OF VANE STACKING**

Variation of the airfoil stacking axis to produce a truly three-dimensional design was used extensively by other researchers over very many years [1]. Such airfoils are meant to capitalize on the three-dimensionality of the underlying flowfield, and they are now used commonly in both turbines and compressors. In the vast majority of applications available in the literature [21-26], whether one considers bowed or leaned airfoils, the aim of varying the stacking axis is to improve aerodynamic performance. In this instance, the design goal is quite different. Here, the emphasis is on the alteration of the magnitude and/or phase of unsteadiness on the blade due to shock reflection from the downstream vane.

When a transonic blade row rotates, the shock waves that extend downstream from the trailing edge move relative to the stationary airfoils downstream. These moving shocks induce small amounts of flow in the direction normal to the shock front [27]. When this induced flow impacts the pressure side of the downstream vane, an equal-and-opposite flow is induced in the vicinity of the stationary surface to maintain the no-slip condition: a shock wave is reflected. This reflected shock travels back upstream to impact the suction side of a neighboring rotating turbine blade [9-10]. Of primary importance is the component of the induced flow normal to the stationary vane. Accordingly, if one were to alter the local surface normal vector of the vane, then by definition the shock reflection itself is altered. Such a change in the local surface of the vane implies an alteration to the three-dimensional shape of the airfoil. That is, it implies a change to the stacking axis.

Initially, the downstream vane profiles were defined at five spans (0, 25, 50, 75, and 100%), and the stacking axis was defined to pass through the centroids of area of all the airfoil cross-sections. This resulted in the “Baseline” downstream vane shown in Fig. 2a and used in previous studies [9, 10]. Note that in the figure, a 3D oblique view of the vane is shown with a nominally aft-looking-forward direction. To test the hypothesis that stacking would alter the shock-induced unsteadiness, the centroid of area of each of the five profiles defining the baseline vane was allowed to shift circumferentially by a small amount of the local pitch (See Table 1). A small shift toward the suction side of the neighboring vane defined the “Initial Bowed” airfoil (Fig. 2b) and was considered positive whereas a comparable displacement toward the pressure side of the adjacent airfoil was “Reverse Bowed” (Fig. 2c). This distinction is important since various usages of the terms are found in the literature. Sometimes authors define positive bow as akin to the deformation an airfoil experiences due to the tangential load on the vane [1]. Other times, such an airfoil is said to have a “lean” or “compound lean” depending on the shape of the final airfoil.

In any case, 3D shaping of the vane was found to have a marked effect on the unsteadiness at the blade suction side downstream of the throat. Fig. 3a is a plot of Discrete Fourier Transform (DFT) magnitudes in terms of percent stage-inlet total pressure at the frequency associated with shocks reflected from the downstream vane. Again, as reported in [9, 10] the dominant frequency on the blade in this region is twice the downstream fundamental frequency (2x23N/60) which corresponds to the 46th Engine Order (46E). As in Fig. 2, an oblique view of the airfoil is shown with a nominal aft-looking-
forward direction. Note that bowing of the downstream vane acts to concentrate the unsteadiness at the blade root (Fig. 3b). Conversely, reverse bowing the vane shifts the unsteadiness toward the blade tip (Fig 3c). From the point of view of resonant stresses [5], concentrating the unsteadiness toward the root of the blade would reduce the work-per-cycle associated with the vibration since modal displacements would be low in that area. Reverse-bowing would have the opposite effect.

![Baseline and Initial Bowed](image1)

![Reverse Bowed and Final Bowed](image2)

**Fig. 2** Downstream vane stacking configurations assessed in this study. The view is nominally aft-looking-forward, and the colorization is the DFT magnitude of the fundamental upstream passing frequency.

Note that in Fig 2, the airfoil surfaces are also colorized to indicate the DFT magnitude at 46E as a percentage of stage-inlet total pressure. For the downstream vane, 46E is the fundamental passing frequency of the upstream blade. One can see that there is little difference in the magnitude of the 46E unsteady pressure on the downstream vane pressure side. This is an indication that the upstream blade shock strength and location is not changed by 3D shaping of the downstream vane. So, the unsteadiness incident to the vane is unchanged (Fig 2a-c). However, the unsteadiness reflected back to the blade (Fig 3a-c) is altered considerably by downstream vane shaping.

Since bowing the airfoil a small amount resulted in a significant change in the unsteadiness on the blade suction side, a design optimization process was implemented to concentrate further the unsteadiness toward the blade root. Complete details of the optimization are found in [28]. In summary, Latin-Hypersquare Sampling (LHS) was used to define an initial population of bowed vanes where only displacements toward the neighboring-airfoil suction side were allowed. The four spanwise sections above the root were each allowed to shift by up to 20% of the local pitch relative to the nearest profile at a lower radius. Then, these airfoils were assessed through 3D time-resolved RANS simulations to determine the unsteadiness on the blade suction side downstream of the throat due to the unique shape of each vane. At that point, a genetic algorithm was used to determine the “fitness” of each vane in a total population of forty eight individuals and to define the next set of vane candidates for assessment through a process that mimicked natural selection. A “fit” vane was one that concentrated the unsteadiness toward the root of the upstream vane while also varying the phase of the unsteadiness over the span. Overall, 424 vanes were assessed through this process to define the final vane depicted in Fig. 2d.

<table>
<thead>
<tr>
<th>Span (%)</th>
<th>Baseline</th>
<th>Initial Bowed</th>
<th>Reverse-Bowed</th>
<th>Final Bowed</th>
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<tr>
<td>0</td>
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<td>0.00</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>5</td>
<td>-5</td>
<td>0.95</td>
</tr>
<tr>
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<td>15</td>
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<td>0</td>
<td>20</td>
<td>-20</td>
<td>44.8</td>
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One can see that the “Final Bowed” vane depicted in Fig. 2d is very effective at concentrating the unsteadiness toward the root of the blade suction side by inspection of the results presented in Fig. 3d. It is also clear from Fig. 4b that the final bowed vane resulted in a much greater range in phase angles over the span of the blade than was found for the baseline vane (Fig. 4a). Note that while a genetic algorithm was used to explore the design space for airfoil bowing, and although the fitness of the vane increased markedly through 16 generations, it is not quite proper to state that the vane was optimized. In practice, the application of the genetic algorithm was halted at a point when the predicted unsteadiness on the blade suction side was modified in keeping with the design goals but also had the potential for meaningful experimental verification. That is, it was halted when it was possible to show that the DFT magnitude was reduced at high span and increased near the blade root. The final bowed vane was selected for fabrication because it met those criteria, although there was some indication that the genetic algorithm might allow for complete eradication of the shock reflection [28].
The effect of downstream vane bowing on predicted row losses in the stage-and-one-half turbine was not significant. Loss results are presented in Table 2 as deltas from those predicted in the baseline rig. The losses are calculated as a percentage change in total pressure from the inlet to the exit of the airfoil row, where the total pressures used are both time- and passage-averaged values that are then mixed out to obtain the final estimates. Note that there is no change to the loss in the inlet guide vane, and this is expected since the first vane is unchanged in any analysis. However, there is some change in both the blade and downstream vane losses due to 3D stacking. For the proof-of-concept airfoils, there is a trade between positive and negative delta losses for the blade and downstream vane. For the final bowed airfoil, the loss increases for both the blade and downstream vane. However, in all cases the delta losses are small enough where the change in rig performance as a consequence of implementing the 3D stacking axis is not large enough to resolve experimentally. This point is discussed further in the section on experimental verification below.

The original and still best investigation on the effects of asymmetric spacing on blade stresses is due to Kemp et al. [17]. They investigated the effects of asymmetric vane spacing in demonstrator engines from a simple consideration of Fourier methods. They considered four different means of achieving non-uniform airfoil spacing. In the first method, they used airfoil passages of a single constant pitch, but they offset two or three segments of the airfoils by some amount. In the second, they analyzed turbine vane rings that were comprised of airfoils with two or three separate pitches. In the third, they considered vanes of randomly-perturbed pitch. Finally, they considered vane rings that were defined based on some combination of the first three methods. They found that the second method was most fruitful, and they confirmed their analytical predictions through engine demonstrator experiments.

While no other study in the literature is as detailed or complete as that of Kemp et al. [17], the use of asymmetric airfoil spacing has become fairly widespread subsequent to that pioneering work. However, it is not often that a study of asymmetric spacing effects concludes with engine verification experiments, but there are exceptions [29]. And although the original study of Kemp et al. concerned a turbine application, compressor implementations of non-uniform pitch are more common nowadays [30-33]. That said, there are recent applications in turbines [34, 35] that included the effect of

<table>
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<th></th>
<th>Baseline</th>
<th>Initial Bowed</th>
<th>Reverse Bowed</th>
<th>Final Bowed</th>
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</thead>
<tbody>
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<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>1B Δ Loss (% Ptin)</td>
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<td>2V Δ Loss (% Ptin)</td>
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<td>0.19</td>
<td>-0.06</td>
<td>0.15</td>
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**Table 2 Row loss delta variations for the different vane stackings considered.**
asymmetric spacing as predicted by modern fluid-structural-interaction methods. One notable finding of turbine studies is that the application of asymmetric spacing is not necessarily beneficial for the reduction of unsteady forcing. For example, it is tempting economically to achieve asymmetric spacing by reducing the airfoil count in a given row. However, a reduction in count leads to an increase in loading on each airfoil that can negate the benefits of non-uniform pitch [29].

Often there are simplifications made to enable the analysis of asymmetric spacing to occur in a timely manner during the design cycle. These run the gamut from simple rule-of-thumb analyses guided by Fourier analysis as in the study of Kemp et al. [17] to the use of airfoil scaling in separate RANS analyses of turbines with different airfoil counts where full-wheel unsteady signals are assembled in post-processing [29]. Here, no such simplifications were made. The asymmetric analyses here were conducted as full-wheel unsteady RANS simulations of the turbine with a downstream asymmetric vane row. The original profile shapes and airfoil count of the vane row (23) was maintained: one half of the vane ring was comprised of airfoils with 22-count spacing, whereas the vanes in the other half of the wheel had a 24-count pitch.

It is important to note that, unlike in the case of airfoil bowing, the intent of asymmetric spacing is not to lower the unsteadiness occurring on the blade overall. Instead, it is to redistribute the unsteadiness occurring at 46E on the blade due to the baseline vane to neighboring frequencies. This is best illustrated by applying Parseval’s theorem in signal processing [36] to the time-resolved pressure distribution on the blade suction side. In fig. 5 mean-square unsteadiness levels for static pressures on the blade due to both symmetrically-spaced vanes (Fig. 5a) and asymmetric vanes (Fig. 5b) are shown. Note that the total unsteady signal power as expressed by the mean-square pressure variations is very consistent between constant and non-uniform pitch vanes. Further, consider integration of the power spectral densities of the local unsteady pressures on the blades over a range of frequencies consistent with the downstream-vane interaction (41E-51E). These are presented in Fig. 6a and 6b for the baseline and asymmetric vanes, respectively. Again, the majority of the unsteadiness is concentrated over that frequency range, although it is clear that there must be additional frequencies arising in the asymmetric case as evidenced by the discrepancies between Fig. 6a and 6b.

Again, the point of asymmetric spacing is to redistribute the 46E unsteadiness due to shock reflections occurring with the baseline vane to additional frequencies. This result is achieved quite successfully in this instance. Consider the set of DFT magnitude plots presented in Fig. 7. The 46E unsteadiness distributions due to baseline and asymmetrically-spaced downstream vanes are given in Fig. 7a and 7b, respectively. The 46E unsteadiness is dramatically reduced by the introduction of asymmetric spacing. More significant unsteady interaction occurs at 44E (Fig. 7c) and 48E (Fig. 7d), and these are consistent with the first harmonics associated with the 22- and 24-count sections of the downstream vane row. The magnitudes of the 44E, 46E, and 48E pressure variations are all significantly reduced relative to the baseline level due to the downstream asymmetric 23-count vane row.

![Fig. 5 Overall unsteadiness on the blade suction side as indicated by the local mean-square of unsteady pressure fluctuations.](image1)

![Fig. 6 Percentage of the overall mean-square unsteadiness due to frequencies associated with shock reflections.](image2)

### EXPERIMENTAL VERIFICATION

Since both downstream vane bowing and asymmetric spacing were very effective with respect to manipulating the unsteady pressure field on the turbine blade row, both methods were selected for verification in a stage-and-one-half transonic turbine experiment. A set of bowed vanes was fabricated and instrumented with piezo-resistive pressure transducers. Likewise, inner- and outer-diameter endwalls with asymmetric spacing were fabricated and instrumented. Because the vanes were manufactured as singlets without endwalls attached, it was possible to build the turbine experimental vane hardware modularly to assess the separate effects of bowing and asymmetric spacing. However, for verification experiments...
considered here, both bowed and asymmetrically-spaced vanes were installed at the same time. Fig. 8a is an engineering drawing of the bowed, asymmetric vane row with a view that is forward-looking-aft, whereas Fig. 8b is a picture of the instrumented vane row prior to installation in the Turbine Research Facility. As seen in Fig. 8a, the upper half of the vane ring relative to top-dead-center contains 12 bowed vanes with 24-count spacing. The lower portion is comprised of 11 bowed vanes with 22-count spacing.

Clearly from Fig. 8b the vane row was very heavily instrumented, so the physics of the shock interaction in the vane passages was very well resolved. However, what is of most relevance here is the effect of airfoil bow and asymmetric spacing on the unsteadiness at the blade suction side. An interrogation of the unsteady vane pressure field is the subject of a future study. Here the entire focus is on the predicted- and measured unsteadiness on the blade suction side.

The experiments described in [9, 10] were repeated with the re-designed vane ring installed as the exit guide vane of the stage-and-one-half transonic turbine. Turbine boundary conditions were consistent with the baseline experiments [9], and the unsteady analysis was as described completely in [10] for blueprint-geometry vanes and blades. All experimental unsteady pressure data were ensemble-averaged [37] over approximately 100 revolutions. The ensemble-averaging operation provided a convenient way to compare Fourier components from periodic-unsteady predictions to those measured in the experiments at the same engine order. Ensemble averaging the signals in this way also acted to window the signals on a time-scale consistent with the rate-of-rotation of the wheel. Consequently, the spectral resolution of the experimental data becomes 1E [36], and the redistribution of signal power due to asymmetric spacing should become readily apparent.

Figure 9 is a set of predicted DFT magnitudes on the blade at 46E for both the baseline vane (9a) and the bowed, asymmetric vane ring (9b) at turbine experimental conditions. Also shown are DFT magnitude variations at 44E (9c) and 48E (9d) due to the bowed, asymmetric vane. Note that there are some discrepancies between the predictions presented in Fig. 9a as compared to Fig. 7a. Two differences in the setups of the separate analyses used to make the plots account for the discrepancies. One is that the geometric grid counts are refined in Fig. 9a relative to those used in the design studies. The grid counts used for the comparison back to experimental data are consistent with those deemed necessary for quantitative comparisons in [9] and [10]. Also, the boundary conditions for
the final comparison are now consistent with the measurements in terms of dynamically-similar conditions. For the re-design studies above, the initial design conditions of the turbine stage were used instead. In any case, for the purposes of comparing experiments to predictions, the results depicted in Fig. 9 are of primary importance. As expected from the design-study calculations, bowing tends to drive the unsteadiness toward the blade root whereas asymmetric spacing tends to re-distribute the unsteadiness from the 46E frequency to neighboring frequencies (44E and 48E). Also, DFT magnitudes seen in Fig. 9b-9d are largely in keeping with a superposition of the effects of bowing and asymmetric spacing on blade unsteadiness.

Note that in fig. 10 four sets of DFT magnitudes are presented for each sensor, and these include two sets of simulation results and two sets of experimental results. The results for the baseline simulation [9] are presented in black, whereas those from the bowed, asymmetric calculation are given in blue. The two sets of experimental data are presented with the baseline data in red and the bowed, asymmetric data in green. Care was taken to ensure that the spectral resolutions for each of the data sets presented in the figure are equal to 1E. Since the spectral resolution of a given signal is the inverse of the total time sampled [36], this was achieved for the experiments by ensemble-averaging the experimental results on a revolution-by-revolution basis. For the simulations, it was necessary to post-process the bowed, asymmetric simulations over a full revolution of the blade row, so the spectral resolution of that data is naturally 1E. However, for the baseline simulation, the flowfield is periodic over the passage of a single vane, so additional post-processing beyond the period of one airfoil passing is usually unnecessary. Still, for the purpose of this comparison, the baseline simulation was post-processed over an entire revolution of the blade row.

Before contrasting the results of the baseline and bowed asymmetric vanes, it is worthwhile to consider how the experimental and simulation results for the baseline compare. Everywhere there is a sensor to indicate the magnitude of unsteadiness at 46E on the blade suction side due to the baseline vanes, the results of the simulation are larger than what was measured in the experiments. This means that any resonant-stress prediction made from the simulation results of the baseline geometry is somewhat conservative. That is, it is likely that measured resonant stresses would be smaller than those predicted, and that is good news from the perspective of the structural and durability designer. Still, at locations where shocks reflected from the downstream vanes can influence the blade unsteadiness (sensors 1, 2, 5-7, and 9), the measured DFT magnitude at 46E might still be larger than is desired.

It is also important to note that some of the DFT magnitude variations presented in fig. 10 are from sensors (3, 4, 8, and 10) that are located in the region upstream of the blade throat. In this region, the pressure variations are a consequence of potential-field and wake-unsteadiness from passage of the upstream vane relative to the blade. Since no design change was made with respect to the upstream vanes, one would expect no change in either the measured or the predicted DFT magnitudes in that region. The data presented is in keeping with that expectation. Comparing the results of the baseline simulation to those of the bowed, asymmetric simulation, one finds that the magnitudes at 46E are unaffected by the change to the downstream vane, and there is therefore no redistribution the blade root whereas asymmetric spacing tends to re-distribute the unsteadiness from the 46E frequency to neighboring frequencies (44E and 48E). Also, DFT magnitudes seen in Fig. 9b-9d are largely in keeping with a superposition of the effects of bowing and asymmetric spacing on blade unsteadiness.

Figure 10 is a set of DFT magnitude variations at locations on the blade suction side where data from both the baseline experiments and those with the bowed, asymmetric vane were available. Experimental locations on the blade consistent with the signals are indicated based on an arbitrary sensor number defined for these comparisons and plotted on the airfoils in Fig. 9. As stated previously, the turbine airfoils used in these experiments were very heavily instrumented. Seventy five piezo-resistive sensors were distributed among the blades in the rotating row. However, a comparison between the effects of the baseline and the bowed, asymmetric vanes on the unsteadiness on the blade suction side requires the existence of data at common locations on the blade during both experiments. Unfortunately, in the final analysis only ten sensors were suitable for such a comparison, and all available data are presented here on fig.10.

The results depicted in Fig. 9 are a set of DFT magnitude variations at locations on the blade suction side at the first harmonic of the downstream passing frequencies for the baseline (a) and bowed, asymmetric vane configurations (b-d) at experimental conditions.

![Fig. 9 DFT magnitudes on the blade suction side at the first harmonic of the downstream passing frequencies](image-url)

For the simulations, the flowfield is periodic over the passage of a single vane, so additional post-processing beyond the period of one airfoil passing is usually unnecessary. Still, for the purpose of this comparison, the baseline simulation was post-processed over an entire revolution of the blade row. Before contrasting the results of the baseline and bowed asymmetric vanes, it is worthwhile to consider how the experimental and simulation results for the baseline compare. Everywhere there is a sensor to indicate the magnitude of unsteadiness at 46E on the blade suction side due to the baseline vanes, the results of the simulation are larger than what was measured in the experiments. This means that any resonant-stress prediction made from the simulation results of the baseline geometry is somewhat conservative. That is, it is likely that measured resonant stresses would be smaller than those predicted, and that is good news from the perspective of the structural and durability designer. Still, at locations where shocks reflected from the downstream vanes can influence the blade unsteadiness (sensors 1, 2, 5-7, and 9), the measured DFT magnitude at 46E might still be larger than is desired.

It is also important to note that some of the DFT magnitude variations presented in fig. 10 are from sensors (3, 4, 8, and 10) that are located in the region upstream of the blade throat. In this region, the pressure variations are a consequence of potential-field and wake-unsteadiness from passage of the upstream vane relative to the blade. Since no design change was made with respect to the upstream vanes, one would expect no change in either the measured or the predicted DFT magnitudes in that region. The data presented is in keeping with that expectation. Comparing the results of the baseline simulation to those of the bowed, asymmetric simulation, one finds that the magnitudes at 46E are unaffected by the change to the downstream vane, and there is therefore no redistribution.
of signal power to the 44E and 48E frequencies. Likewise, a comparison of measured DFT magnitudes from the baseline turbine to the experimental results from the bowed, asymmetric vanes is indicative of neither a change in the size of fluctuations nor a redistribution of signal power to other frequencies.

By contrast, compare the baseline and bowed, asymmetric-vane measurements of DFT magnitudes on sensors located downstream of the blade throat (1, 2, 5-7, and 9), where the effects of shock interactions from the downstream vane predominate. In all cases, the 46E unsteadiness found in the baseline results is distributed to the 44E and 48E frequencies. It is also clear that at the outer span (sensors 1 and 2), the combination of bowing and asymmetric spacing acts to reduce the unsteadiness overall. Conversely, in the lower spans (sensors 5-7 and 9) the unsteadiness due to the bowed, asymmetric airfoils is increased overall. That is, taking the results of all sensors (i.e. 1, 2, 5-7, and 9), bowing acts effectively to concentrate the unsteady pressure to the blade root, where modal displacements and work per vibratory cycle would be relatively small. Also, asymmetric vane spacing acts to redistribute the unsteady signal power that would occur at 46E to neighboring frequencies at 44E and 48E. This is especially apparent at the location where the unsteadiness is at its highest (i.e. sensor 9). So, the overall intent of the design changes applied to the downstream vane is verified experimentally.

That said, there are some differences between the results of the bowed, asymmetric vane simulation and the experiment that are interesting. At sensors 6 and 7, the simulation results indicated that significant signal power associated with the 46E unsteadiness would not re-distribute to the 44E and 48E frequencies. This is also discernible from a close examination of fig. 9b in the regions around the locations of sensors 6 and 7. By contrast, the experimental results indicated that asymmetric spacing was as effective at those sensor locations as elsewhere in terms of the redistribution of unsteady signal power. One notes that the region of high unsteadiness on fig. 9b is consistent with the impingement location of the cross-channel shock on the suction side. It is conceivable that in the simulation, some oscillation of the shock location is tied to the potential field of the upstream vane, whereas that effect is absent in the experiments. At any rate, one can conclude from the comparison of measurements and simulations that the bowed, asymmetric vane is more effective at splitting the 46E unsteadiness into neighboring frequencies than predictions would indicate.

It is worth revisiting the question of a potential trade-off between the manipulation of unsteady forcing and the consequent effect, if any, on aero-performance. The full-scale turbine facility at AFRL is designed primarily to evaluate unsteady aerodynamics and heat transfer of rotating airfoil components. As such, it is not an adiabatic facility that is conducive to evaluating small loss deltas due to design changes like those of interest here (See Table 2). In addition, while there are rotating total-pressure and total-temperature rakes in the experiment, they occur only at the inlet and exit to the stage-and-one-half turbine.

So, the best that one can do is to evaluate the change in turbine efficiency considering all three rows, which one could define as an “indicated rig efficiency.” For the final simulations described here, the predicted decrement in indicated rig efficiency that occurs as a consequence of implementing the bowed, asymmetric vane row is just 0.1%. That is a very small performance impact, and it is certainly offset by the improvement in turbine durability that would arise as a consequence of the reduced unsteadiness. This is especially true when one considers that a decrease in resonant stress from one demonstrator engine test to another can make all the difference in engine certification. That said, the difference in indicated rig efficiency as calculated from time- and area-averaged rake instrumentation between the baseline and bowed, asymmetric vane configuration was also of order 0.1%. However, one must stress that considering the small changes involved, this result should be characterized as anecdotal.

CONCLUSIONS

Design changes relative to the downstream vane in a stage- and-one-half transonic turbine were suggested and analyzed through the level of time-resolved RANS analysis in an effort to demonstrate the mitigation of unsteady pressures due to reflected shocks in such a system. It was predicted that bowing the downstream vane toward the suction side of the neighboring vane acted to concentrate the unsteady pressures due to reflected shocks in the vicinity of the blade root. It was also predicted that the use of asymmetric airfoil spacing in the downstream airfoil row would act to redistribute the unsteady signal power from the baseline vane to neighboring frequencies. Following these design studies modular turbine experimental hardware was constructed and tested in a verification experiment that combined both bowed airfoils and asymmetric spacing. It was found that the effects of airfoil bow and asymmetric spacing were very well predicted both qualitatively and quantitatively. Accordingly, the use of airfoil bow and asymmetric spacing in combination is a viable course of action to solve resonant stress problems encountered in the development of future turbines of like configuration.

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Fig. 10 A comparison of measured and simulated DFT magnitudes on the blade suction side at frequencies around the first harmonic of the downstream passing frequencies for the baseline and bowed, asymmetric vane configurations.

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