THE USE OF CIRCUMFERENTIALLY NONUNIFORM STATORS TO ATTENUATE LP COMPRESSOR ROTOR-STATOR-STRUT AERODYNAMIC AND MECHANICAL INTERACTIONS

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ABSTRACT
A potential flow computer model that can handle blade row interaction problem has been used to analyze the circumferential static pressure distribution at the trailing edge plane of the last rotor in an axial compressor which is produced by a downstream stator/strut system. The computer model is based on the Douglas-Neumann formulation. The code was used to design a circumferentially nonuniform stagger angle distribution for the stator that reduced the static pressure disturbance on the rotor. The predicted circumferential static pressure distribution and its resulting frequency content at the rotor trailing edge station for the baseline (uniform circumferential stagger angles) stator and for the optimized stator are compared to static pressure data and derived frequency content from engine tests of each configuration. The results show good agreement between the model predictions and the test data. The results are further confirmed by measurements of rotor strain levels with the baseline stator and with the optimized stator, which show a proportional decrease in rotor strain for the optimized stator configuration. Since incorporation of this low-cost modification, there has been no evidence of vibratory induced rotor distress, thereby improving engine reliability and maintainability and enhancing customer satisfaction.

INTRODUCTION
Structural or service struts crossing the fan and/or compressor floor paths in aircraft gas turbine engines generate potential flow disturbances that propagate throughout the flowfield. The effect of the strut potential field on upstream and downstream components is exaggerated by a requirement of minimum axial spacing in aircraft engines. These potential field disturbances, in the form of circumferentially varying pressure levels, result in high noise levels or in forces that can excite vibration in upstream rotating blade rows (McArdle et al. (1983), Preiss et al. (1981), Ho (1981), O'Brien et al. (1983), Woodward and Balombin (1984), Nakamura et al. (1986), Cerri and O'Brien (1989), and Shinivas and Giles (1995)).

Several investigators have shown that a stator positioned axially between a strut or struts, and an upstream rotor may be configured to shield the rotor from the potential flow disturbances of the struts or struts. Rubbert et al. (1972) developed a concept of circumferentially varying the stator vane camber angles in the region of a thick strut to shield the rotor from the strut pressure disturbance. The analysis was supported by various 2- and 3-D potential flow analysis methods, but no testing was performed to prove the concept. This type of stator modification is generally unattractive unless the configuration is amenable to casting due to the costs associated with manufacturing a stator cascade that uses more than one blade type.

Yokoi et al. (1981) proposed circumferentially restaggering the stator vanes in the vicinity of six struts that were positioned downstream of a fan stage. The analysis method modeled the stator as an array of straight one-dimensional diffusers. Several restagger patterns were tested, showing large reductions in the upstream pressure disturbance (in good agreement with the analytical model) and sizable reductions in rotor strain levels. However, neither the circumferential position of the stator vanes relative to the struts, the stator loading, or the stator incidence was considered in the optimization.

Cerri and O'Brien (1989) performed a detailed investigation of the concept of circumferentially varying stagger angles in the region of a thick strut to reduce the upstream pressure disturbance. A 2-D flow model based on the classical Douglas-Neumann singularity superposition method was used to solve the cascade/strut system in an assumed potential flowfield. This model was used to develop optimal restaggered stator configurations that reduced the analytically-predicted pressure disturbance from the stator/strut combination to a level approaching the disturbance produced by the
develop the restaggered stator. They were developed at Virginia Polytechnic Institute and State University and are based on the classical Douglas-Neumann singularity superposition method (Ceri and O'Brien, 1989). This model can handle multiple cascade analysis and is thus suitable for blade row interaction investigations.

**OPTIMIZATION PROCESS AND CRITERIA**

During the design a number of stator configurations were evaluated. Perturbations in stator stagger level and its circumferential distribution as well as stator position relative to the downstream struts were evaluated with the computational model. The primary optimization criteria were minimum harmful frequency content and minimum circumferential rotor exit plane Ps(max)-Ps(min) with acceptable stator aerodynamic loadings and incidence. The intent of this criteria was to minimize rotor response while assuring acceptable performance. The final configuration, which in this paper is referred to as optimum, was that which best satisfied these criteria. Mathematical optimization techniques were not used so stator configurations likely exist which would result in lower rotor excitation.

Aerodynamic performance potential and risk were evaluated by examining the flow distributions around the stator vanes and by examining and comparing the model-calculated inviscid stator loadings. In this process, particular emphasis was placed on the incidence and airfoil surface loading distributions of the stator vanes in close proximity to the struts.
Thin Strut Pattern

Thick Strut Pattern

Fig. 2. Selectively Restaggered Stator Configuration.

Figure 3 shows analytically derived flow visualization plots for the stator vanes located adjacent to the thick strut for the baseline stator and for the optimized restaggered stator. Note the large change in incidence for the vanes located immediately on either side of the strut centerline in the baseline stator. This incidence variation is caused by circumferential distribution of stator passage flow rates that results from the downstream strut blockage and resulting potential field. The restaggered stator exhibits a more uniform circumferential incidence distribution.

A corresponding large circumferential variation in vane loading is evident in the model results for the baseline stator/thick strut, with a much more uniform distribution for the restaggered stator (Fig. 4). In addition to stator vane stagger angle, the position of the vane trailing edges (relative to the strut) of the two vanes located immediately adjacent to the strut plays a role in achieving a more equal loading split between these vanes. Figure 5 compares the loadings for these two vanes for the baseline vane clocking (strut centerline located halfway between the vane trailing edges) and for the optimal clocking (strut centerline located at 30 percent of the vane trailing edge gap, with the strut centerline being closest to the trailing edge of the vane in the direction of rotor rotation). While these discussions and figures have illustrated our results for the single thick strut, similar trends and conclusions were drawn for the three thin struts.

The reduction in rotor excitation was quantified by calculating the reduction in the magnitude of the predicted circumferential rotor exit plane $P_{\text{max}} - P_{\text{min}}$ value (the ‘height’ of the bump in the circumferential static pressure distribution upstream of the vane) and by performing Fourier (frequency content) analysis of this static pressure distribution. Reducing the magnitude of the upstream pressure disturbance is paramount, but it is potentially as important to control the shape of the disturbance, as the shape of the static pressure disturbance determines its frequency content. Figure 6 illustrates that the rotor in this study has a first bending mode resonance with the eighth engine order (8E) that occurs well within the limits of the operating speed range. Reduction of the strut-induced 8E excitation, itself a harmonic of the primary strut 4E excitation, was therefore a primary goal of the stator optimization.

Figure 7 shows the analytically predicted reductions in the rotor exit plane circumferential static pressure distribution $P_{\text{max}} - P_{\text{min}}$ for the thick strut and for the thin strut. Figure 8 shows the corresponding predicted reduction in frequency content (especially 8E content) as calculated by Fourier analysis of the analytical pressure profiles.
**Fig. 3.** Baseline and Restaggered Stator Flowfield Comparison for the Thick Strut.

**Fig. 4.** Calculated Stator Loadings for the Four Stators Nearest the Thick Strut for Both the Baseline and Restaggered Configurations.

**Fig. 5.** Effect on Stator Loading of Stator/Strut Relative Circumferential Position for the Stators Nearest the Thick Strut.
The reduction in Ps(max)-Ps(min) that is attained was found to be a direct function of the magnitude of the vane restagger, which is limited by vane loading and incidence considerations. The control of the frequency content (achieved by tailoring the shape of the circumferential static pressure distribution) is a direct function of the circumferential extent of the restagger pattern. Experience shows that control of the frequency content of the pressure disturbance can be at least as important as a reduction in the magnitude of the disturbance.

During the analytical study, it was observed that the stagger angle modifications required to minimize the strut pressure disturbance and frequency content were generally similar to the

**Fig. 6. Compressor Rotor Blade Campbell Diagram.**

**Fig. 7. Model Predicted Rotor Exit Plane Circumferential Static Pressure Distributions.**

**Fig. 8. Harmonic Content Comparison Between the Baseline Stator Model and the Restaggered Stator Model, Using Predicted Rotor Exit Plane Circumferential Static Pressure Profiles.**
stagger angle modifications that were required to optimize the circumferential distribution of stator vane incidence and loading in the vicinity of a downstream strut. This conclusion was drawn from observation of the flow vector plots and stator loadings for stators near the struts which resulted as struts were modified to minimize the rotor exit static pressure distribution. Therefore, the restaggered stator appears to be an optimal design on both aeromechanical and blade row performance counts. Indeed, comparison of the vane incidence and loadings of the baseline stator to the incidence and loadings of the restaggered stator suggests that the blade row performance of the restaggered stator will exceed the performance of the baseline design.

ENGINE TEST ARTICLES, INSTRUMENTATION, AND TEST

The stator row for this particular engine configuration consists of stators that are only moderately three-dimensional and are positioned in the flowpath by precision slots laser drilled in hub and shroud rings. In order to implement the restagger, it was only necessary to modify the programming for the machine that laser cut the slots for the baseline stator configuration. This allowed design, procurement and test of the restaggered stator in only a few months and resulted in a part that was essentially the same cost as the original part. In addition, the tested part became the final production part with only the addition of a simple “Murphy proof” feature which positively located the stator restagger pattern relative to the struts.

Two engine tests were performed to determine the success of the restaggered stator in reducing the upstream static pressure disturbance that is caused by the downstream struts. The first test established levels of rotor strain and static pressure for the baseline (uniformly staggered) stator. The second test used the optimized restaggered stator. Strain gages were installed on the rotor and static pressure taps were installed in the stator shroud in the plane of the leading and trailing edge of the stator. This instrumentation was used to measure the effect of each stator configuration on the rotor exit static pressure distortion, excitation, and response. Except for the stator, the configuration of the development engine for the two tests was identical. In the discussions, the plane which includes the static pressure taps in the stator shroud at the stator leading edge is referred to as the rotor exit plane.

The locations of the shroud static pressure taps for both the thick and the thin struts are shown in Fig. 2 for the restaggered stator configuration. Static pressure taps for the baseline configuration were located similarly. As shown, the static pressure taps were located at mid pitch, relative to the stator. This was done in order to minimize the impact of the stator static pressure field on our deduction of the change in strut induced static pressure field for the two configurations. Due to practical limitations associated with engine testing, incorporation of sufficient statics to investigate the pitchwise variation in stator static pressure field was not possible. The trailing edge static pressure taps were installed to help detect the presence of airflow separation in the vane passages near the struts. Leading edge and trailing edge static pressure taps were also installed midway between the four struts. These “free-stream” measurements allowed performance comparisons between the baseline and restaggered stators to be performed. In the engine tests, the stators located in front of all four struts were instrumented in an identical manner. Twelve strain gages were installed on 12 different rotor blades to assure adequate sampling of the rotor strain. The gages were positioned to measure the first bending mode.

ENGINE TEST RESULTS

The test of the restaggered optimized stator was successful. Rotor strain levels were reduced an average of 59 percent compared to strain levels measured for the rotor with the baseline stator. Engine operability and performance were nominal, to marginally improved throughout the operating speed range. There was no evidence in the static pressure data of airflow separation in the restaggered stator. Figure 9 shows the measured rotor exit plane, shroud, circumferential static pressure profiles for the baseline stator and for the restaggered stator in the region of the thick strut and in the region of the thin strut. The percent reductions in $P_s(max) - P_s(min)$ show very good agreement with the model predictions shown in Fig. 7. Fourier analysis of the complete tested circumferential rotor exit plane, shroud, static pressure profiles confirmed a seventy-eight 78 percent reduction in 8E frequency content for the restaggered stator compared to the baseline stator with the results illustrated in Fig. 10. The mid-strut stator leading edge and trailing edge static pressure data show that the restaggered stator had improved recovery as compared to the baseline stator, as evidenced by its improved static pressure rise characteristics as shown in Fig. 11. Table 1 is a brief summary of various model predictions compared with test results.

<table>
<thead>
<tr>
<th>Model Predictions</th>
<th>vs Test Results</th>
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<tbody>
<tr>
<td>Percent reduction in 8/E frequency content</td>
<td>72</td>
</tr>
<tr>
<td>Percent reduction in thick strut ($P_{s\text{max}} - P_{s\text{min}}$)</td>
<td>50</td>
</tr>
<tr>
<td>Percent reduction in thin strut ($P_{s\text{max}} - P_{s\text{min}}$)</td>
<td>57</td>
</tr>
<tr>
<td>Percent reduction in Rotor strain</td>
<td>-</td>
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<tr>
<td>Percent increase in Stator static pressure rise</td>
<td>-</td>
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Early in this work, when the baseline test was run and before design of the restaggered stator, it became clear that the model predicted $P_{s\text{max}} - P_{s\text{min}}$ was larger than indicated by the test data. This was true for both the thick and thin struts and can be seen by comparing the predictions of Fig. 7 to the test data of Fig. 9. There are many possible explanations for this, both on the analysis side, (potential flow, steady, mean streamtube) and on the data side (non high response, position and size of the static pressure taps in a highly nonuniform pressure field) among many others. The data and the analysis, together, seemed to support that the change in the rotor exit static pressure disturbance was directly proportional to the change in the potential field. Given this, the decision was made to proceed forward with the assumption that the model would do a good job of predicting the relative change in the rotor exit static pressure fields.
SUMMARY AND CONCLUSIONS
An optimized restaggered stator was designed that reduces the upstream static pressure disturbance on a rotor arising from the presence of downstream struts. The restagger patterns were developed with the aid of a 2-D potential flow formulation based on the Douglas-Neumann singularity superposition method. Back-to-
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REFERENCES


