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INVESTIGATION OF THE EFFECTS OF INLET SWIRL ON COMPRESSOR PERFORMANCE AND OPERABILITY USING A MODIFIED PARALLEL COMPRESSOR MODEL*

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ABSTRACT

Serpentine ducts used by both military and commercial aircraft can generate significant flow angularity and total pressure distortion at the engine face. Most low by-pass ratio turbofan engines with mixed exhaust are equipped with inlet guide vanes (IGV) which can reduce the effect of moderate inlet distortion. High by-pass ratio and some low by-pass ratio turbofan engines are not equipped with IGVs, and swirl can in effect change the angle of attack of the fan blades.

Swirl and total pressure distortion at the engine inlet will impact engine performance, operability, and durability. The impact on the engine performance and operability must be quantified to ensure safe operation of the aircraft and propulsion system. Testing is performed at a limited number of discrete points inside the propulsion system flight envelope where it is believed the engine is most sensitive to the inlet distortion in order to quantify these effects. Turbine engine compressor models are based on the limited amount of experimental data collected during testing. These models can be used as an analysis tool to improve the effectiveness of engine testing and to improve understanding of engine response to inlet distortion.

The Dynamic Turbine Engine Compressor Code (DYNTECC) utilizes parallel compressor theory and quasi-one-dimensional Euler equations to determine compressor performance. In its standard form, DYNTECC uses user supplied characteristic stage maps in order to calculate stage forces and shaft work for use in the momentum and energy equations. These maps were typically developed using experimental data or created using characteristic codes such as the 1-D Mean Line Code (MLC) or the 2-D Streamline Curvature Code. The MLC was created to calculate the performance of individual compressor stages and requires less computational effort than the 2-D and 3-D models.

To improve efficiency and accuracy, the MLC has been incorporated into DYNTECC as a subroutine. Rather than independently developing stage maps using the MLC and then importing these maps into DYNTECC, DYNTECC can now use the MLC to develop the required stage characteristic for the desired operating point. This will reduce time and complexity required to analyze the effects of inlet swirl on compressor performance. The combined DYNTECC/MLC was used in the past to model total pressure distortion. This paper presents the result obtained using the combined DYNTECC/MLC to model the effects of various types of inlet swirl on F109 fan performance and operability for the first time.

INTRODUCTION

Turbine engines generate thrust by compressing incoming air in the inlet and compressor, mixing that air with fuel and igniting the air/fuel mixture in the combustor, then expanding the high pressure and temperature air through a turbine and nozzle. Though centrifugal compressors are used in smaller engines, most large military and commercial turbine engines use axial flow compressors [1]. Axial flow compressors compress the air by passing it through a series of rotating airfoils called rotor blades and stationary airfoils called stator vanes. Rotor blades have an incidence angle which is the angle between the velocity of the flow relative to the rotor blade and the camber line at the leading edge of the rotor blade. Compressor performance and operability are affected by defects in the pressure and temperature of the incoming flow, also known as pressure and temperature distortion as well as flow angularity. If the pressure ratio across the compressor is raised high enough, or if the incidence angle of the rotor blades becomes too large, flow over the rotor blades will separate from the suction surface resulting in stall [2].

The entrance to a turbine engine compressor is often referred to as the aerodynamic interface plane (AIP). Flow angularity at the AIP can have both radial and circumferential velocity components. Of these two components, the circumferential component of the absolute velocity vector (often referred to as swirl) has the strongest effect on compressor performance because the angle of this component has a direct impact on the incidence angle of the rotor blade [3].

The Society of Automotive Engineers (SAE) has published a guideline to address engine inlet total pressure spatial distortion, ARP 1420 [4]. This guideline is supplemented by SAE Aerospace Information Report AIR1419 [5] and additional reports have been issued by the SAE S-16 committee regarding inlet planar waves [6] and inlet temperature distortion [7]. The SAE has also published a report detailing the different types of swirl that can form at the AIP, AIR 5686 [8]. This report contains detailed information regarding the different swirl patterns discussed in this paper as well as additional swirl patterns that can develop at the AIP. Davis, Hale, and Beale [9] have made an argument for the enhancement of ground test techniques in order to better simulate swirl at the AIP of an engine in flight citing the effect of inlet swirl on engine performance and operability. Several methods for simulating inlet swirl in turbine engine ground tests are under development at the Arnold Engineering Development Center (AEDC) [10, 11]. Evaluating the effect of inlet swirl on turbine engine compressor performance during ground tests would reveal engine performance and operability issues before initial flight testing which would ensure safe operation of the engine/aircraft and avoid costly airframe and engine inlet modifications.

The analysis presented in the paper focused on two types of swirl: bulk swirl and paired swirl. Bulk swirl is shown in Figure 1 and consists of a flow that is rotating either in the same direction relative to the compressor rotation (co-swirl) or in the opposite direction relative to the compressor rotation (counter-swirl).

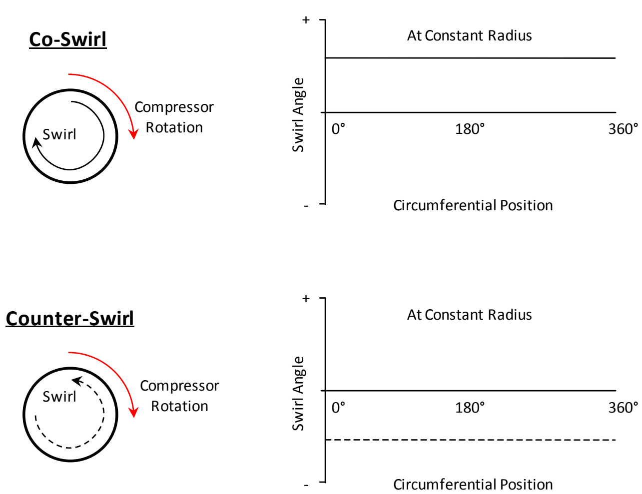

Figure 1. Bulk Swirl

In the case of bulk swirl, the entire flow field at the AIP is rotating in the same direction. Paired swirl, shown in Figure 2, is composed of two vortices rotating in opposite directions. One vortex is a co-swirl vortex while the other is a counter-swirl vortex. If the two vortices are symmetric, then the paired swirl is referred to as twin swirl, else it is referred to as offset swirl.

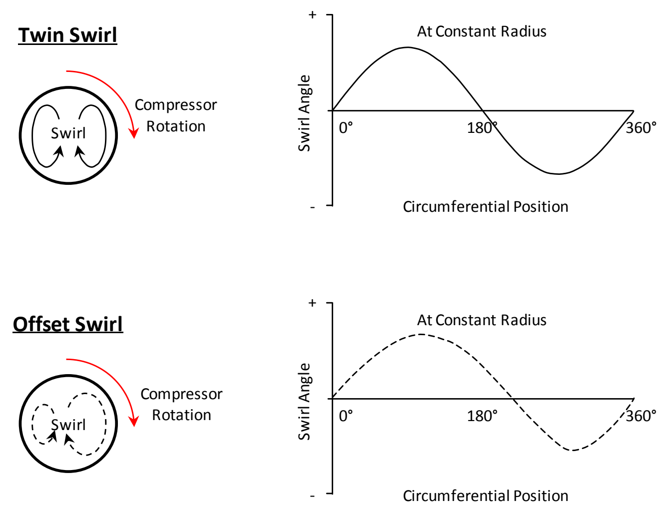

Figure 2. Paired Swirl

IGVs are used to change the angle of the flow entering the compressor at the AIP. When operating properly, IGVs will add co-swirl ($\alpha > 0$) to the flow which will move the compressor away from stall. In the past it was not necessary to simulate swirl at the AIP of a turbine engine during ground testing because of the relatively straight inlet systems and the incorporation of IGVs into turbine engine designs. Current aircraft designs may incorporate S-ducts with sharp bends into the engine inlet systems in order to hide the engine face from radar waves. Investigations have been performed in order to characterize the effects the S-ducts have on the flow properties at the AIP of turbine engines. These studies have shown that flow separation in the S-duct results in swirl at the AIP [12]. In some cases, the swirl can be severe enough to cause flow separation on the IGVs which effects engine operability [13]. Engines without IGVs, such as most high by-pass ratio turbofan engines, are more sensitive to swirl at the AIP than those with IGVs. This is because swirl will change the incidence angle of the first stage compressor blades on the engine.

The impact of swirl on the engine performance and operability must be quantified to ensure safe operation of the aircraft and propulsion system. The test points can be optimized using turbine engine compressor models that are validated using experimental data gathered at a limited number of discrete operating points inside the engine flight envelope.

Total pressure distortion and swirl at the AIP of a turbine engine are often interdependent and areas of high swirl correspond to areas of low total pressure [3]. Compressor models can be used to decouple total pressure distortion and swirl such that the effect of swirl alone on compressor performance and operability can be evaluated. This would be very difficult to do in a test environment but is a relatively simple input for a compressor model.

A parallel compressor model is often used in the study of inlet distortion. Parallel compressor models sub-divide compressor control volumes into parallel or circumferential segments that can have different inlet boundary conditions. Each segment acts separately but in parallel with each other and exit to the same boundary condition [13]. An illustration of the parallel compressor theory concept is shown in Figure 3.

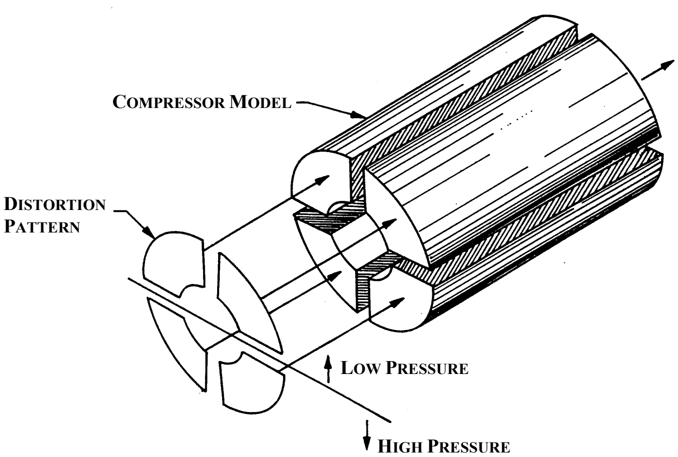

Figure 3. Parallel Compressor Theory Concept [16]

Parallel compressor models require source terms such as blade forces, shaft work, bleed flows, and energy addition or subtraction due to heat transfer in order to properly model the compression system [14]. Source terms are most often provided in the form of compressor characteristic maps. In these maps, the pressure and temperature rise across the compressor is supplied as a function of corrected mass flow and corrected speed. These maps are typically developed using experimental data. If experimental data is unavailable, characteristic maps can be created using characteristic compressor codes such as the MLC or the 2-D Streamline Curvature Code [15].

The compressor characteristic maps required to run the parallel compressor models present an inherent disadvantage when attempting to model inlet swirl. As mentioned previously, compressor performance is dependent upon the incidence angle of the rotor blades. The presence of swirl at the AIP will change the incidence angle of the first stage rotor blades on turbine engines that are not equipped with IGVs. The change in incidence angle will result in a change in the relationship between the pressure and temperature rise across the compressor and the corrected mass flow and corrected speed of the compressor. When swirl is present, new compressor characteristic maps must be developed that include the effects of swirl [13].

In the past, compressor characteristic maps were developed for different cases of swirl. These maps were layered together as a function of swirl angle. Should the inlet conditions to the compressor change, data from the compressor characteristic maps can interpolated to obtain the stage characteristic data at the desired inlet condition. The development of the layered characteristic maps increases the time and effort needed to model swirl while interpolation of the layered maps increases uncertainty in the final output.

Rather than develop layered compressor characteristic maps outside of the parallel compressor code for different cases of swirl, a faster and more efficient method would be to develop the source terms for the model using a subroutine called the parallel compressor model. This approach also increases the accuracy of the model output because stage characteristic behavior is determined for the case being studied thus eliminating the need for interpolation. In 2003, Tibboel integrated a one-dimensional compressor stage characteristics code into a parallel compressor code called DYNTECC and used the code to model the effect of pressure distortion on compressor performance [16]. The work documented in Ref. 16 demonstrated the ability to use the MLC as a subroutine to DYNTECC, but analysis of the effect of swirl on compressor performance and operability was not performed.

The objective of the research reported herein was to integrate the MLC into DYNTECC as a subroutine and use the combined DYNTECC/MLC to model the effect of different types of swirl on F109 fan performance and operability. This work was based on the work performed by Tibboel, but additional effort was required in order to address DYNTECC stall criteria and the additional inputs required to analyze swirl [16]. The combined DYNTECC/MLC was then used for the first time to model inlet swirl. A brief description of the F109 can be found in Ref. 16.

INTEGRATION OF THE 1-D MLC INTO DYNTECC

The integration of the MLC into DYNTECC as a subroutine was based on the work of Tibboel [16]. During normal operation (Figure 4), DYNTECC uses the stage characteristic maps to determine stage pressure and temperature ratio as a function of corrected speed and corrected flow. In addition, a stall criterion is built into DYNTECC which uses the shape of the pressure characteristic. DYNTECC analyzes the slope of the pressure stage characteristic, and when the slope reaches zero, DYNTECC indicates that the stage has then become stalled.

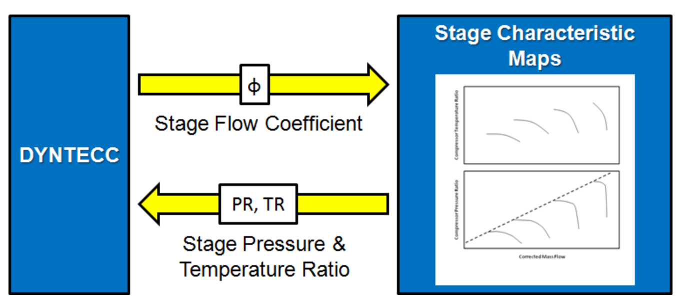

Figure 4. Nominal Operation of DYNTECC Using Defined Stage Characteristic Maps

When operating with the MLC, characteristic maps were not used. Inputs necessary for the MLC were passed from DYNTECC in subroutine fashion to the MLC which then calculated the necessary pressure ratio (PR) and temperature ratio (TR) required by DYNTECC, as illustrated in Figure 5. Stall was not defined in the MLC and as a result the MLC was modified to output a notification when the stage reaches the stability limit. Rotor diffusion factor (D_r) is a measure of velocity diffusion on the suction side of a rotor blade and can be correlated directly with total pressure loss [1]. Diffusion factor can also be used as a measure of blade loading.

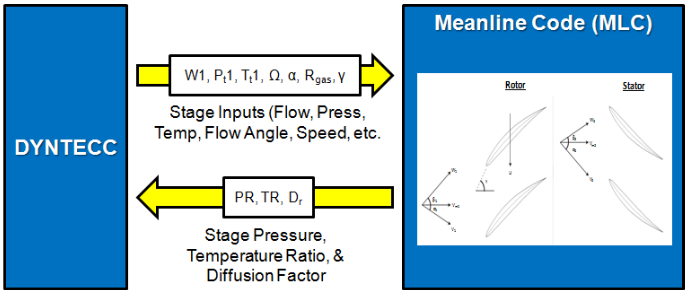

Figure 5. Operation of DYNTECC Using a MLC to Provide Local Stage Pressure and Temperature Characteristic Information at Each Time Step

The MLC was modified to calculate and output rotor diffusion factor. This task was made easier by the fact that the MLC already calculated and output all of the parameters necessary to calculate rotor diffusion factor. DYNTECC was modified to compare the diffusion factor output by the MLC with a user specified stalling diffusion factor and quit executing when the number of stages indicating stall reaches a user defined limit, thus indicating system stall.

In lieu of specific blade characteristic information, the MLC uses a set of loss and deviation correlations to determine blade pressure rise and turning. These correlations were developed by Hearsey [17] using NACA 65 series, vand double circular arc blade experimental data from NASA SP-36 [18]. However, during the process of adapting these correlations to the F109 fan compressor, it was noted that the output of the Hearsey correlations was significantly degraded and the add-loss and add-deviation adjustment to the correlations were unrealistic. Thus an option was added to by-pass the Hearsey correlations in the MLC and instead look-up values of rotor and stator relative total pressure loss and blade exit deviation angle from 2-D tables.

The MLC was used in a standalone mode to develop the rotor and stator total pressure loss and blade exit deviation angle tables. An overall F109 fan map was used to provide mass flow and stage characteristics at the following fan speeds (percent of design fan speed): 20%, 45%, 60%, 70%, 80%, 85%, 90%, 95%, 100%, 105%, 110%, and 115%. Normally, in order to calibrate the MLC, PR and TR for each stage must be known, but since the F109 fan is a single stage fan this map could be used.

Initially, actual clean inlet test data obtained at the United States Air Force Academy (USAFA) in 2008 was to be used to calibrate the MLC. The USAFA data was obtained at only four fan speeds: 53%, 62%, 71% and 84%. The fan temperature ratio measured at the USAFA was less than the isentropic fan temperature ratio that corresponded to the measured fan pressure ratio and was deemed invalid.

The pressure loss and exit deviation output from the MLC during the calibration process was plotted as a function of incidence angle and inlet relative Mach number and a surface was fit to the output in order to aid in extrapolation and provide evenly space grid points. Two-dimensional tables for rotor relative total pressure loss, rotor exit deviation angle, stator relative total pressure loss, and stator exit deviation angle were built using the surface fit to the MLC output. The rotor relative total pressure loss and blade exit deviation angles output by the MLC as well as the surface fit used to extrapolate and build the two-dimensional look-up tables are shown in Figures 6 and 7.

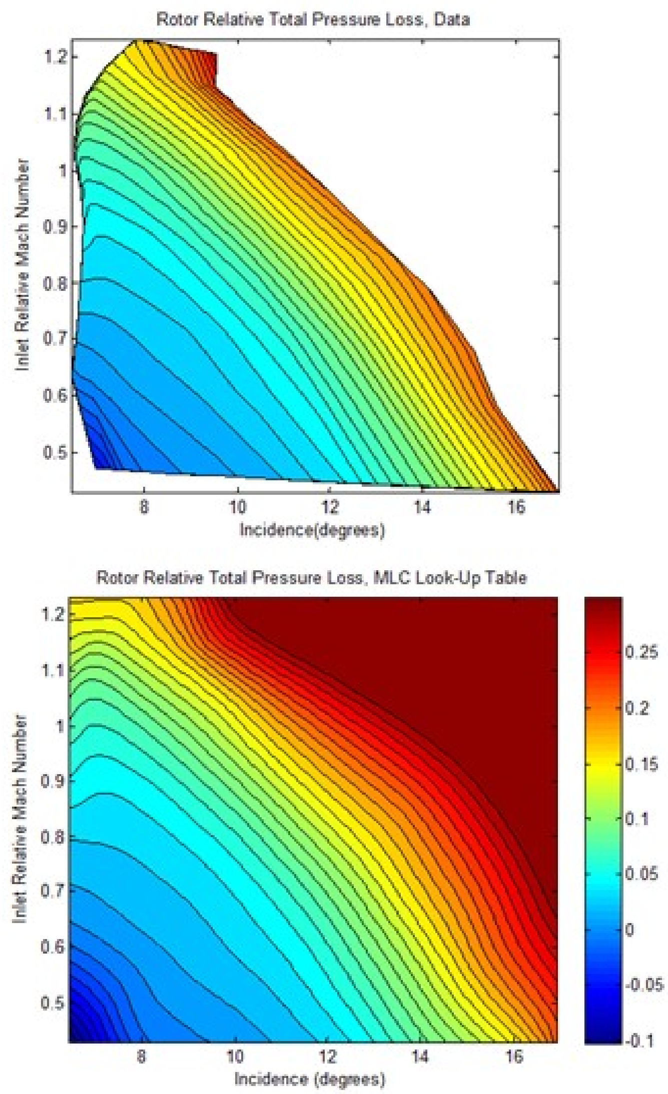

Figure 6. Relative Total Pressure Loss

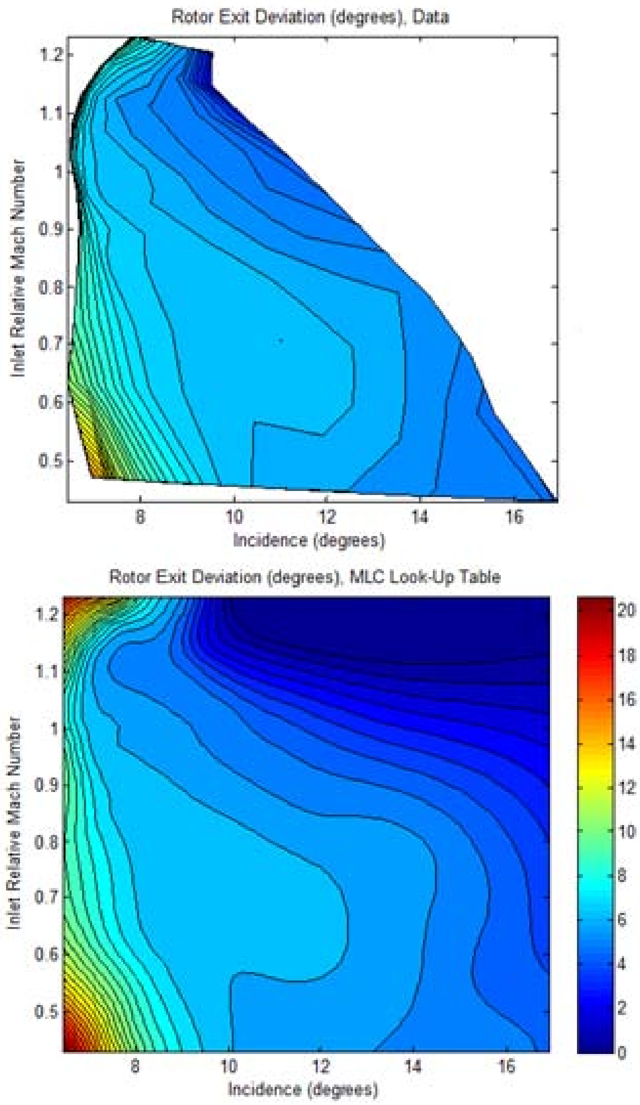

Figure 7. Relative Rotor Deviation

Total pressure loss across a cascade is a function of blade incidence angle and inlet Mach number [18]. The rotor and stator relative total pressure loss and exit deviation angle were treated as a function of inlet relative Mach number and blade incidence angle because in the relative reference frame, rotating blades are treated as a cascade.

Stator Loss and Deviation were calculated similarly using a 1 percent loss across the stator and no deviation. As mentioned earlier, the rotor diffusion factor was used to determine stall. Figure 8, shows the rotor diffusion factor along the F109 cycle deck stall line as calculated by the MLC. The average of the stalling diffusion at each constant speed line in the F109 cycle deck was used as the DYNTECC user specified stalling diffusion factor.

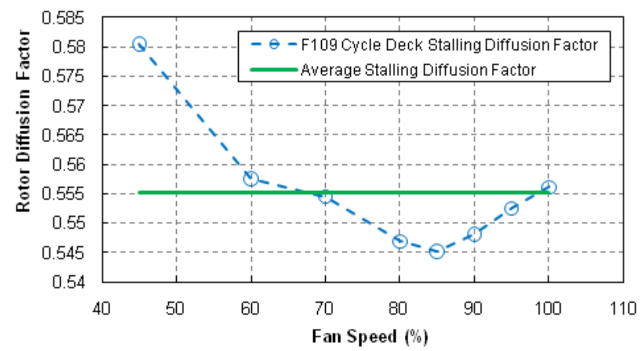

Figure 8. F109 Overall Map Stall Line Rotor Diffusion Factor

COMBINED DYNTECC/MLC OPERATING PROCEDURE

DYNTECC is formulated as an initial condition boundary value problem. Initial conditions for the dependent variables are provided by an internal steady state stacking routine. Major inputs to the stacking routine are included in the data input file and geometry file. These inputs include the corrected rotational speed of the rotor, the initial airflow rate, and the boundary condition type and magnitude. A set of initial conditions for control volume entrance is calculated using steady-state flow physics and pre-stall compressor stage characteristics. This allows a steady flow situation from which the dynamic model starts.

Time dependent boundary conditions can be specified either at the entrance or the exit of the overall control volume. Inlet total pressure or temperature time history may be linearly ramped, varied cyclically, or remain constant. The same is true for the overall control volume exit pressure, Mach number, and airflow rate. At the entrance, both total pressure and total temperature must be specified. At the exit, however, only one of these parameters should be specified. The other parameter is set depending on the type of exit boundary condition selected in the data input file.

The following procedure was used to investigate the effects of swirl on system performance and operability. The parallel compressor model was first allowed to come to a steady condition using a constant exit Mach number boundary condition associated with the operating point of interest. When swirl was implemented on the system, it was initiated instantaneously after the steady condition was established. This caused some numerical instability which quickly settled out and the system was allowed to reach a new steady condition again. Once steady conditions were assured, the exit Mach number which had been held constant for steady operation was decreased at a quasi-steady rate to back pressure the system and drive the system to its instability point. The system stability limit was determined by a particular value of diffusion factor as outlined in a previous section. Once the limiting diffusion factor was reached DYNTECC terminated execution even if the desired decrease in Mach number had not been achieved.

VALIDATION OF COMBINED DYNTECC/ MLC

Before beginning the analysis of F109 fan performance with swirl at the AIP, it was important to verify that the DYNTECC/MLC predicted fan performance was in acceptable agreement with the F109 cycle deck and the experimental data obtained at the USAFA over the entire range of operating speeds. Figure 9 is a comparison of the constant speed lines generated by the combined DYNTECC/MLC and the steady state speeds line from the F109 cycle deck used to generate the loss and deviation look-up tables for the MLC. The DYNTECC/MLC prediction was within ±0.5% of the F109 cycle deck for all speed lines, showing excellent agreement. Figure 10 is a comparison of the DYNTECC/MLC predicted speed lines with constant speed lines measured at the USAFA.

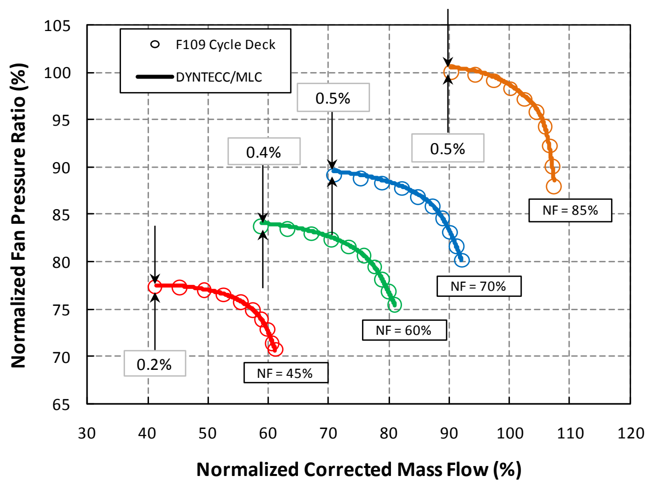

Figure 9. DYNTECC/MLC Predicted and F109 Cycle Deck Specified Fan Map Comparison (No Swirl)

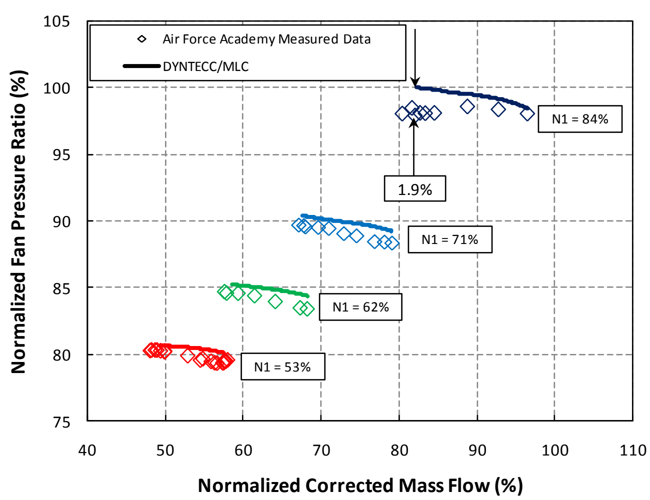

Figure 10. DYNTECC/MLC Predicted and USAFA Measured Fan Map Comparison (No Swirl)

The DYNTECC/MLC prediction was within ±0.8% for all speed lines except the 84% fan speed line, showing reasonable agreement. The fan speed of the measured data was not a constant 84% during data acquisitions and may not be a valid constant speed line.

Before evaluating the effects of inlet swirl on F109 fan operability, it was important to first determine whether the choice of rotor diffusion factor as the stalling criteria was valid. Figure 11 is a comparison of the DYNTECC/MLC predicted stall line and the F109 cycle deck specified fan stall line. The DYNTECC/MLC predicted stall line shows excellent agreement with the F109 cycle deck specified stall line at lower fan speeds. At 84% fan speed, the DYNTECC/MLC stall line was ~1.4% higher than the F109 Cycle deck specified stall line.

Figure 12 is a comparison of the DYNTECC/MLC predicted stall line and the measured fan stall line. The DYNTECC/MLC stall line was within ±0.7% of the measured fan stall line, showing acceptable agreement.

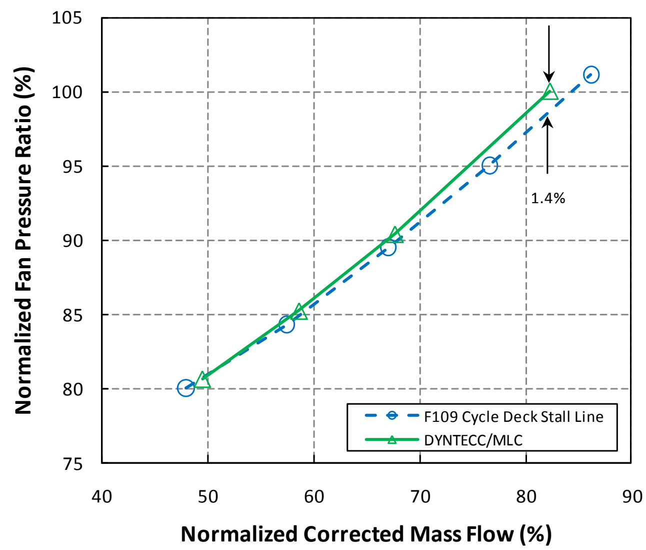

Figure 11. DYNTECC/MLC Predicted and F109 Cycle Deck Specified Fan Stall Line (No Swirl)

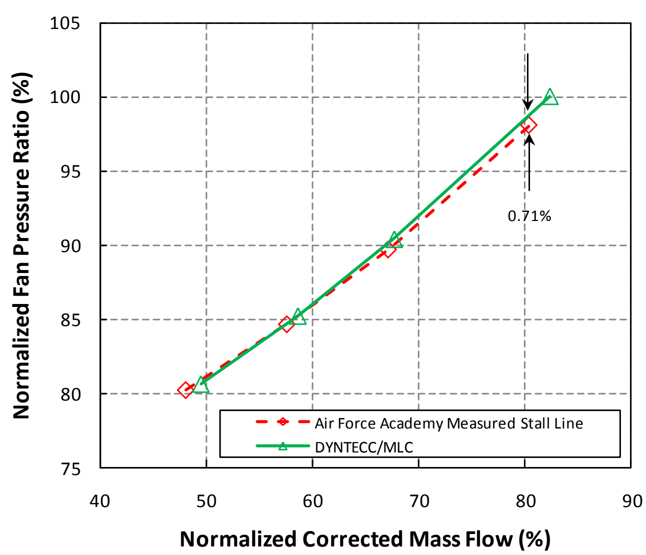

Figure 12. DYNTECC/MLC Predicted and USAFA Measured Fan Stall Line (No Swirl)

PRESENTATION OF RESULTS

The effect of the different swirl patterns modeled at the F109 AIP on the compressor performance will be shown on a compressor map. The compressor map has the ability to show the change in fan pressure ratio and mass flow at a constant speed for each of the different cases modeled. The effect of the different swirl patterns on F109 fan operability will be characterized by the loss in stability pressure ratio (ΔPRS) (shown graphically in Figure 13) is described in Reference 4 as the percent change in stability pressure ratio between the undistorted and distorted stability limit point at a constant corrected mass flow.

A positive value for ΔPRS indicates a loss in stability pressure ratio while a negative value for ΔPRS indicates a gain in stability pressure ratio.

$$\Delta PRS = \left(\frac{PR1 - PRDS}{PR1}\right) * 100$$

Two different types of bulk swirl and one type of paired swirl were analyzed using the combine DYNTECC/MLC. Because both DYNTECC and the MLC are essentially one dimensional, only one value of swirl angle is chosen for each parallel compressor segment in DYNTECC. In reality, swirl angle at the AIP changes with radius. The swirl angle used by the combined DYNTECC/MLC is a notional average swirl angle for the segment. For comparison to experimental data, the combined DYNTECC/MLC would use a root mean square average of the swirl angle across the radius as the input.

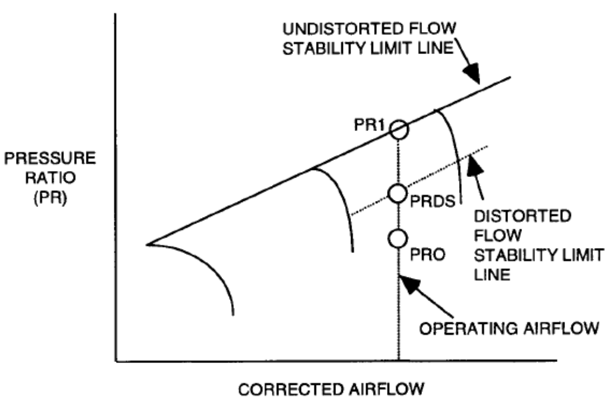

Figure 13. Loss in Stability Pressure Ratio (ΔPRS) [4]

Bulk Swirl

It has been found that bulk swirl can develop at an AIP downstream of an s-duct at a high angle of attack and is a result of flow separation at the lip of the inlet [4]. There are two types of bulk swirl: co-Swirl and counter-swirl. Co-swirl and counter-swirl were modeled using the combined DYNTECC/MLC at three increasing levels of swirl intensity: 5°, 10° and 15°. These intensities were similar to the same intensities modeled in Ref. 18. These swirl levels were evaluated at four different fan speeds: 53%, 62%, 71% and 84%. These speeds correspond to the fan speeds where data was collected at the USAFA. Mach number was used as the back boundary condition for the parallel compressor model.

Figure 14 shows the DYNTECC/MLC prediction of the effect of the varying levels of co-swirl intensity on F109 fan performance and operability. As the intensity of the co-swirl is increased, the fan pressure ratio at a constant referred mass flow decreases. The referred mass flow at the stall point for each fan speed also decreases as co-swirl intensity is increased. At 84% fan speed with 15° co-swirl, the flow through the fan begins to move into the choked region. The decrease in fan pressure ratio and referred mass flow at fan stall resulting from the co-swirl is cause by the reduction in blade loading. The incidence angle of the rotor decreases as the magnitude/intensity of the co-swirl increases. The reduction in rotor incidence angle causes the blade to become unloaded, which decreases the fan pressure ratio and increases the fan stall margin.

The DYNTECC/MLC prediction of the effect of counter-swirl on F109 fan performance and operability is shown in Figure 15. As the intensity of the counter-swirl increases, the fan pressure ratio at a constant referred mass flow increases. The referred mass flow at the stall point for each fan speed also increases as counter-swirl intensity is increased. At 71% fan speed, the referred mass flow at fan stall with 15° counter-swirl is almost the same as the clean inlet steady-state operating point referred mass flow. At the highest F109 fan speed, 84%, the referred mass flow at fan stall is greater than the clean inlet steady-state operating point. This means that the F109 fan would stall if it encountered 15° counter-swirl at 84% fan speed.

The increase in fan pressure ratio and referred mass flow at fan stall resulting from counter-swirl is caused by the increase in blade loading. The incidence angle of the rotor increases as the magnitude/intensity of the counter-swirl increases. The increase in rotor incidence angle causes the blade to become more loaded, which increases the fan pressure ratio and decreases the fan stall margin.

The loss (or gain) in stability pressure ratio is plotted as a function of bulk swirl angle in Figure 16. ΔPRS increases with increasing counter-swirl and decreases with increasing co-swirl. The change in ΔPRS becomes more pronounced as the fan speed increase.

Paired Swirl

When flow separation is not present at the lip of an inlet, a paired swirl pattern will develop at the AIP downstream of an s-duct [19]. Twin paired swirl was modeled using DYNTECC/MLC with two equal segments with 10° of swirl in each segment. DYNTECC divided the fan into two equal parallel tubes. One tube had 10° of co-swirl applied while the other had 10° of counter-swirl applied. The 10° intensity was chosen because that is the intensity that was modeled in Ref. 18. Mach number was used as the back boundary condition for the parallel compressor model.

Figure 17 shows the effect of 10° twin swirl on fan performance and operability predicted by DYNTECC/MLC at 84% referred fan speed. The DYNTECC/MLC prediction for 10° co-swirl and 10° counter-swirl are included in this figure for comparison.

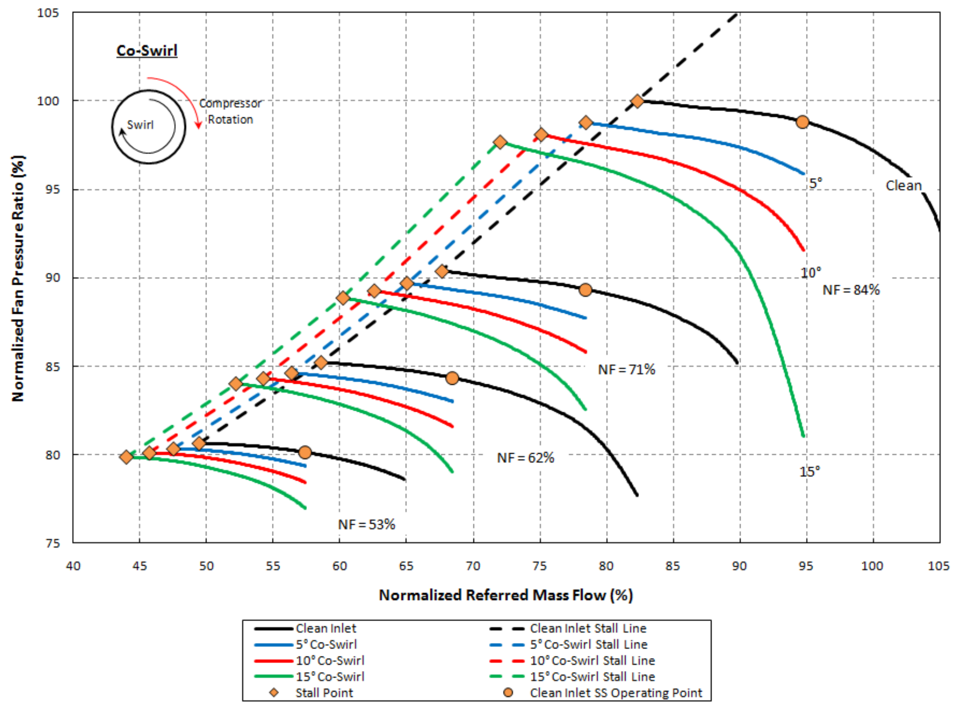

Figure 14. DYNTECC/1-D MLC Prediction of the Effect of Co-Swirl on F109 Fan Performance and Operability

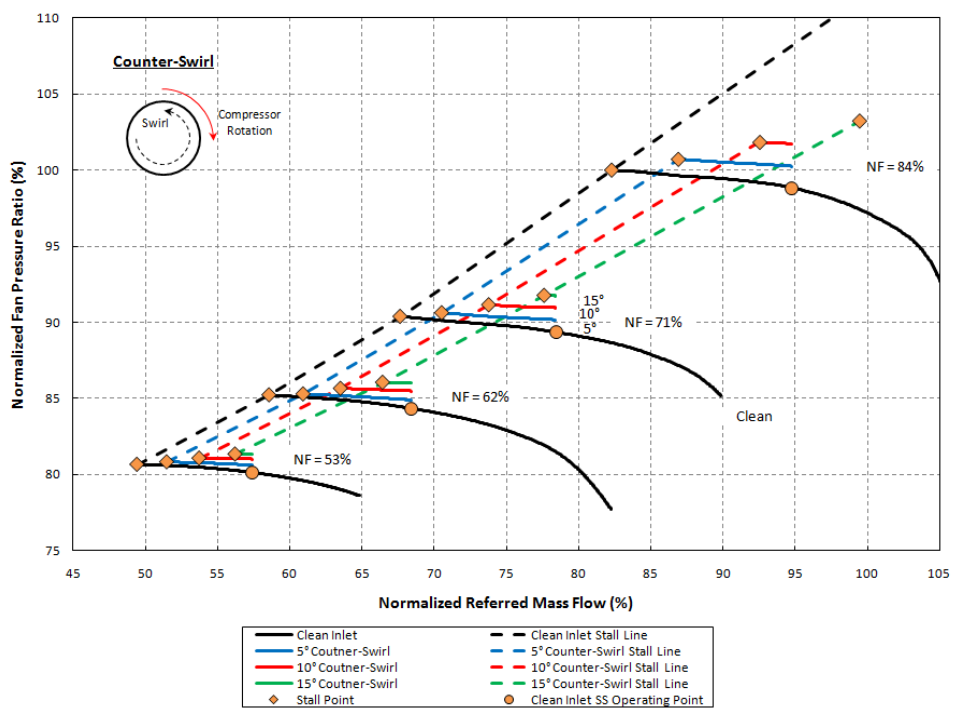

Figure 15. DYNTECC/1-D MLC Prediction of the Effect of Counter-Swirl on F109 Fan Performance and Operability

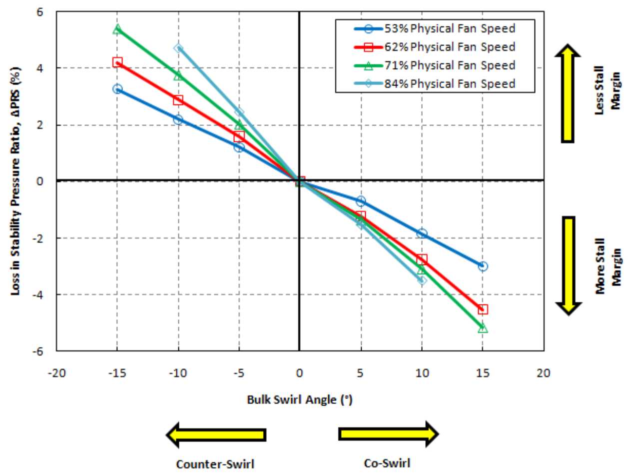

Figure 16. Loss in Stability Pressure Ratio (ΔPRS) as a Function of Bulk Swirl Angle

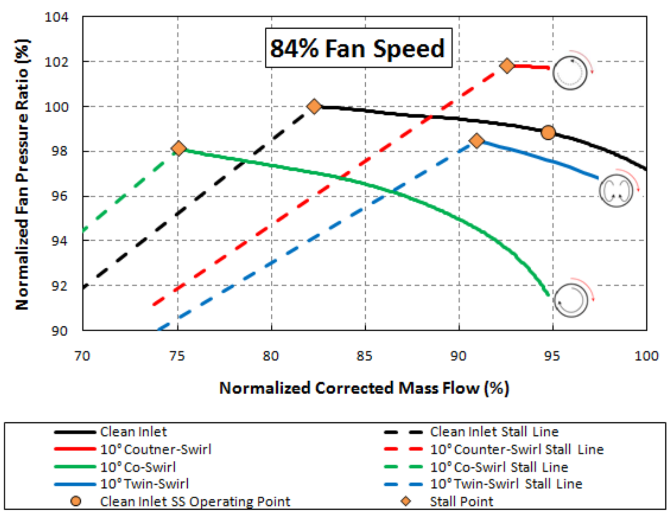

Figure 17. DYNTECC/1-D MLC Prediction of the Effect of 10° Co-Swirl, 10° Counter-Swirl and 10° Twin-Swirl on F109 Fan Performance and Operability at 84% Fan Speed

Twin swirl was also done at other speeds, but not shown. The results at the other speeds are similar to the 84% results.

DYNTECC/MLC predicts that twin-swill will have a combine co- and counter-swill effect on the fan performance and operability. Like co-swirl, twin swirl lowers the fan pressure ratio at a constant pressure ratio relative to the clean inlet case. However, rather than increasing the stall margin, twin swirl decreases the stall margin like counter-swirl. The fan pressure ratio predicted by DYNTECC/MLC for 10° twin-swirl is approximately an average of the fan pressure rise for co- and counter-swirl at the same referred mass flow. This is expected, because half of the compressor is operating at an elevated fan pressure ratio while the other half is operating at a lower fan pressure ratio. The overall fan pressure ratio will be an average of these two separate compressors. Figure 18 shows DYNTECC/MLC predicted ΔPRS as a function of percent referred fan speed for 10° twin-swirl and 10° counter-swirl. Because of the reduced fan pressure ratio coupled with the increased referred mass flow at stall, the ΔPRS increases faster with twin-swirl than with counter-swirl as referred fan speed increases.

The referred mass flow at stall is much less with 10° twin-swirl than with a clean inlet or with 10° co-swirl, but is slight higher than with 10° counter-swirl. The twin-swirl test case becomes stalled once the diffusion factor of the parallel compressor segment with 10° counter-swirl reaches the stalling diffusion factor, shown in Figure 19. This result is different than the result obtained in Ref. 3, Ref. 13 and Ref 19. The model utilized in Ref. 3 and Ref. 19 used static pressure as the back boundary condition, whereas a Mach number was used as the back boundary condition for the research reported herein. These references also used a different stalling criterion. The research presented in these references determined the stall point by comparing the flow coefficient of each segment to a stalling flow coefficient determined for each swirl case. The flow coefficient in these references is indicative of the corrected flow that would exist in that sector if the sector were operating with full flow. These references found that as the exit boundary condition was throttled, the flow coefficient of co-swirl segment was much lower than the flow coefficient of the counter-swirl segment and subsequently reach the calculated stalling flow coefficient. Like Ref. 3, Ref. 13, and Ref. 19, Figure 19 shows that the corrected mass flow of the co-swirl segment is much lower than the corrected mass flow of the counter-swirl segment. Unlike these references, the combined DYNTECC/MLC calculates the diffusion factor for each segment directly and compares it to the user specified stalling diffusion factor.

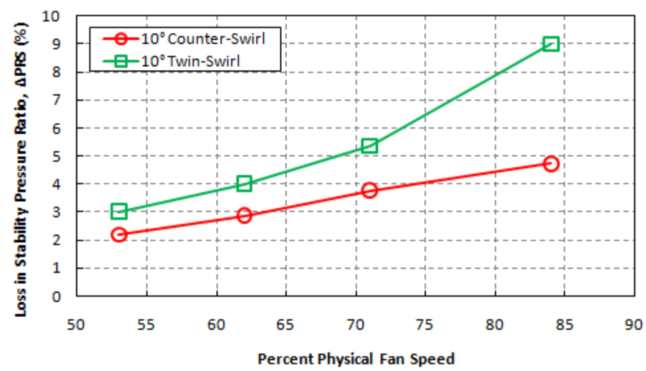

Figure 18. Loss in Stability Pressure Ratio (ΔPRS) as a Function of Percent Referred Fan for 10° Counter-Swirl and 10° Twin-Swirl

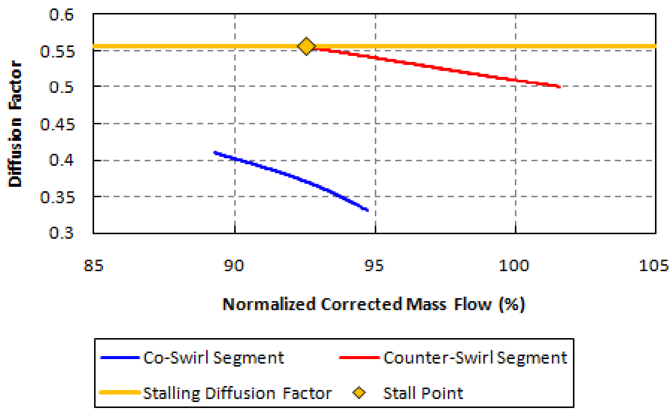

Figure 19. Twin Swirl Segment Diffusion Factor at Constant Fan Speed

SUMMARY AND CONCLUSIONS

A new version of the MLC was incorporated into the parallel compressor model DYNTECC as a subroutine. DYNTECC was able to use the MLC to calculate a point-by-point representation of the stage characteristics internally without the use of characteristic maps. Both DYNTECC and the MLC were modified in order to determine stage stall criteria. The MLC was modified to output a rotor diffusion factor while DYNTECC was modified to compare the rotor diffusion factor to a user specified stalling diffusion factor. Additional modifications were made to the MLC in order to by-pass blade relative total pressure loss and deviation correlation and look up those values directly from a user provided two-dimensional table. Rotor and stator relative total pressure loss and exit deviation angle tables were developed using a standalone version of the MLC operating in a calibration mode. Stage characteristics required for developing the relative total pressure loss and blade exit deviation tables were obtained from the F109 cycle deck.

The combined DYNTECC/MLC was validated by comparing clean inlet predictions to the F109 cycle deck and well as clean inlet data obtained at the USAFA. The DYNTECC/MLC predicted F109 fan pressure ratio was within 0.5% of the F109 cycle deck fan pressure ratio and was generally within 0.8% of the USAFA measured fan pressure ratio at the same referred fan speed and referred mass flow. The clean inlet stall line predicted by the DYNTECC/MLC was compared to the F109 cycle deck stall line as well as the clean inlet stall line measured at the USAFA and showed acceptable agreement with both.

Varying intensities of bulk swirl and paired swirl were modeled using the combined DYNTECC/MLC. Two cases of bulk swirl were modeled: co-swirl and counter-swirl. Each of these cases were modeled at the following swirl angles: 5°, 10° and 15°. In the case of co-swirl, DYNTECC/MLC model predictions showed that as the swirl angle increases, the fan pressure ratio decreases and fan stability margin increases. In the case of counter-swirl, DYNTECC/MLC model predictions showed the opposite. As counter-swirl intensity increases, DYNTECC/MLC predicts that fan pressure ratio will increase while fan stability margin decreases.

Twin swirl was the only case of paired swirl modeled using DYNTECC/MLC. DYNTECC/MLC predicted that twin swirl reduces fan pressure ratio and also reduces fan stability margin.

The loss in stability pressure ratio with 10° twin swirl was compared to the loss in stability pressure ratio with 10° counter-swirl. For the same amount of swirl, the loss in stability pressure ratio was much greater and increased at a higher rate with paired twin-swirl compared to bulk counter-swirl.

Once rotor and stator relative total pressure loss and blade exit deviation tables were developed, modeling different cases of inlet swirl with the combined DYTNECC/Mean code was simplified because new stage characteristic maps did not have to be developed for each case. Modeling a different case of swirl was as easy as changing one or two DYNTECC inputs. No data has yet been gathered for the F109 with swirl at the AIP. Because no data has yet been gathered with swirl at the AIP of an F109, the DYNTECC/MLC predictions for various cases of bulk and paired swirl have not yet been validated.

RECOMMENDATIONS FOR FUTURE WORK

The work reported herein helped further the development of a new tool capable of modeling the effects of inlet swirl at the AIP of an axial flow turbine engine. However, predictions made with the modified DYNTECC/MLC with swirl at the AIP have not yet been validated using measured test data. It is recommended that testing on the F109 with swirl generators be completed so that the DYNTECC/MLC model can be validated.

Another recommendation would be to better understand the consequences of using a one-dimensional model to predict multi-dimensional phenomena. Average compressor stage characteristics were used to develop the relative total pressure loss and blade exit deviation tables, and mean line values of swirl were modeled using the code. Swirl angle changes with radius, and different values of swirl at the hub and tip of the compressor might have an effect on the compressor performance and operability. It should also be noted that the combined DYNTECC/MLC is only capable of modeling a single stage fan or compressor. The capability to model multiple stage compressors should also be pursued.

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