

**Validation of a Modified Parallel Compressor
Model for Prediction of the Effects of Inlet Swirl
on Compressor Performance and Operability**

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

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December 2014

DEDICATION

I would like to dedicate this work to my parents, Reginald and Leona Floyd, for without their constant support and emphasis on continued learning, this would not have been possible.

ACKNOWLEDGEMENTS

I would like to thank all those that helped and provided their support during the preparation of this thesis. First and foremost, I would like to thank Dr. Milt Davis for providing the thesis topic as well as the continuous guidance and assistance during the preparation. His immense knowledge on the subject at hand was invaluable to the process. I would also like to thank Chris Davis for providing countless hours of technical support. His knowledge of the code used in this thesis was a great help to me. I would also like to thank the Major Professor of my thesis committee, Dr. Trevor Moeller, and thesis committee member, Dr. James Simonton. Their support during the preparation of this thesis was vital. I would also like to thank Arnold Air Force Base for providing time and resources to complete this thesis.

ABSTRACT

Engine inlet distortion complications have plagued the turbine engine development community for decades, and engineers have developed countless methods to identify and combat the harmful effects of inlet distortion. One such type of distortion that has gained much attention in recent years is known as inlet swirl, which results in a significant flow angularity at the face of the engine. This flow angularity can affect the pressure rise and flow capacity of the fan or compressor, and subsequently affect compressor and engine performance.

Previous modeling and simulation efforts to predict the effect inlet swirl can have on fan and compressor performance have made great strides, yet still leave a lot to be desired. In particular, a one-dimensional parallel compressor model called DYNTECC (Dynamic Turbine Engine Compressor Code) has been used to analyze the effects of inlet swirl on fan and performance operability of the Honeywell F109 turbofan engine. However, when compared to experimental swirl data gathered at the United States Air Force Academy (USAF), the model predictions were found to be inaccurate.

This thesis documents work done to compare the initial predictions generated by DYNTECC to the latest set of experimental swirl data, analyze the potential shortcomings of the initial model, and modify the existing model to more accurately reflect test data. Extensive work was completed to create a methodology that can calibrate the model to existing clean inlet fan map data. In addition, an in depth study of fan/compressor stalling criteria was conducted, and the model was modified to use an alternate stalling criteria that more accurately

predicted the point of stall for various swirl inlet conditions. The prediction of the fan stall pressure ratio for all inlet swirl conditions tested is within 2% of the ground test stall point at the same referred fan speed and referred mass flow.

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NOMENCLATURE

α	Swirl angle
β_1	Inlet relative flow angle
β_2	Blade exit relative velocity flow angle
β_{1op}	Inlet relative flow angle at operating line (minimum loss condition)
β_{2op}	Blade exit relative velocity flow angle (minimum loss condition)
β_2'	Blade exit metal angle
γ	Ratio of specific heats
δ	Blade exit angle deviation
ΔPRS	Loss in stability pressure ratio
v_1	Blade inlet absolute tangential velocity
v_{1R}	Blade inlet relative tangential velocity
v_2	Blade exit absolute tangential velocity
v_{2R}	Blade exit relative tangential velocity
ρ	Density
σ	Blade solidity
ω	Blade relative total pressure loss
Φ	Pressure loss coefficient
A	Area
AEDC	Arnold Engineering Development Complex
AIP	Aerodynamic interface plane
CFD	Computational fluid dynamics
c_p	Specific heat at constant pressure

C_p	Static pressure rise coefficient
DF	Rotor diffusion factor
DF _m	Rotor diffusion factor (compressibility effect)
DR	Rotor diffusion ratio (stalled condition)
DR _{op}	Rotor diffusion factor (minimum loss condition)
DH	De Haller number
DYNTECC	Dynamic Turbine Engine Compressor Code
E	Energy function
e	Internal energy
F _b	Blade force
F _x	Axial force distribution acting on the control volume
H _B	Total enthalpy of the bleed flow
i	Incidence angle
i _{op}	Incidence angle at operating line (minimum loss condition)
IGV	Inlet guide vanes
IMP	Impulse Function
M _{1R}	Inlet relative Mach Number
MFF	Mass flow function
MLC	1-D Mean Line Code
PR	Stage pressure ratio
PR1	Undistorted stability pressure ratio
PRDS	Distorted stability pressure ratio
P _s	Static pressure

P_1	Blade inlet total pressure
P_2	Blade exit total pressure
Q	Rate of heat addition to the control volume
SW	Rate of shaft work
TR	Stage temperature ratio
T_1	Inlet total temperature
U	Axial velocity vector
U_x	Velocity vector normal to AIP
U_θ	Circumferential velocity vector
U_1	Blade entrance wheel speed
U_2	Blade exit wheel speed
USAFA	United States Air Force Academy
V_1	Blade inlet absolute velocity
V_{1R}	Blade inlet relative velocity
V_2	Blade exit absolute velocity
V_{2R}	Blade exit relative velocity
V_{A1}	Blade inlet axial velocity
V_{A2}	Blade exit axial velocity
W	Mass flow rate
W_B	Inter-stage bleed mass flow per distributed length

1.0 INTRODUCTION

1.1 TURBINE ENGINE MODELING

Modeling and simulation is an integral part of the test and evaluation process currently found throughout the aerospace and turbine engine industry. Modeling and simulation can act as a perfect complement to testing; it can predict outcomes from the test beforehand while also validating and verifying results from the test. A model is a physical, mathematical, or logical representation of a system, entity, or process. The model implemented over some axis of change is known as a simulation. Together, they can provide a powerful tool for learning and decision making in any realm. There are two types of models, empirical and theoretical. Empirical models are based on data or observations of the phenomena under investigation and are probabilistic in nature. Theoretical models are physics-based, derived from an understanding of the theory behind the process under investigation, and are deterministic in nature. DYNTTECC, the modeling and simulation tool at the heart of this work is a hybrid of these two model types, coupling empirical elements with the theoretical base to add precision. DYNTTECC can be used for investigating a host of performance and operability issues plaguing turbine engines of today.

Turbine engines in aerospace applications generate thrust by compressing incoming air in the engine inlet and compressor, mixing the compressed air with fuel and igniting the mixture in the combustor, then expanding the high pressure/temperature air through a turbine and nozzle at the

exit of the engine. Axial flow compressors are the most common type of compressor found in today's larger commercial and military aerospace turbine engines [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 angle of attack called the incidence angle. The incidence angle is the angle between the velocity of the flow relative to the rotor blade and the camber line of the rotor blade [1]. Performance and operability of the compressor is highly dependent on changes in the flow entering the compressor, such as pressure and temperature distortion and flow angularity. If the pressure across the compressor is increased substantially, or if the incidence angle of the rotor blades becomes too great, flow over the rotor blades will separate from the surface to initiate blade stall, which can permeate throughout the compression system and cause damage to the engine.

1.2 INLET SWIRL

One type of inlet distortion quickly becoming relevant to modern turbine engines is inlet swirl. Swirl is defined as the circumferential component of the flow angularity at the face of the compression system. As depicted in Figure 1, the flow angularity in the inlet (α) is defined as the difference between the local velocity vector (U) and a vector normal to the Aerodynamic Interface Plane (U_x). This inlet swirl phenomenon can strongly affect the incidence angle on the rotor (or inlet guide vanes if so equipped), as well as the pressure rise and flow

capacity of the fan or compressor. Swirl has been known to have a strong effect on compressor performance, and can materialize in several forms.

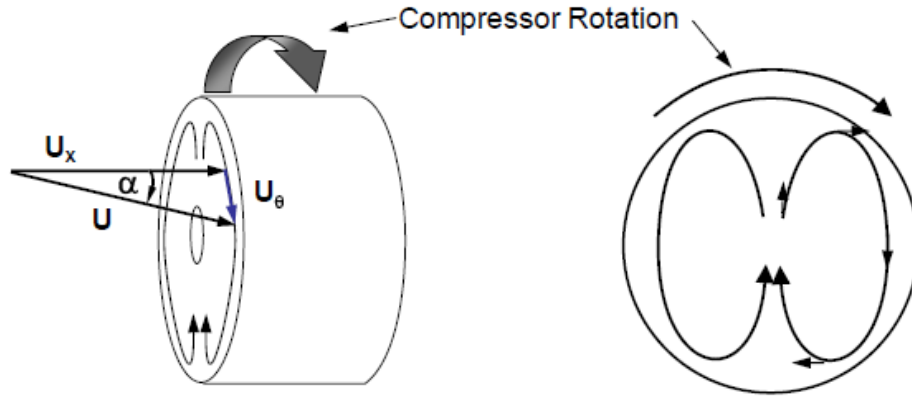


Figure 1. Definition of Swirl Angle

The first type of swirl is known as bulk swirl. Bulk swirl is made up of a singular swirl pattern relative to the AIP, and can come in two forms, co-rotating and counter-rotating [2]. If the incoming flow to the engine is rotating in the same direction as the compressor rotation, it is called a co-rotating swirl, where aerodynamic loading is decreased and the aerodynamic stability margin is increased. If the flow approaching the compressor is rotating in the opposite direction to the compressor rotation, then it is referred to as counter-rotating swirl, where aerodynamic loading increases and the margin of aerodynamic stability is reduced. Paired swirl is the confluence of two bulk swirl patterns (counter-rotating and co-rotating) and is found in two forms, offset and twin [2]. Twin swirl consists of symmetric and opposing swirl patterns, while offset swirl features non-symmetric and opposing swirl patterns. Both cause an increase in

blade loading and reduction in stability margin. Each type of swirl pattern is given in Figure 2.

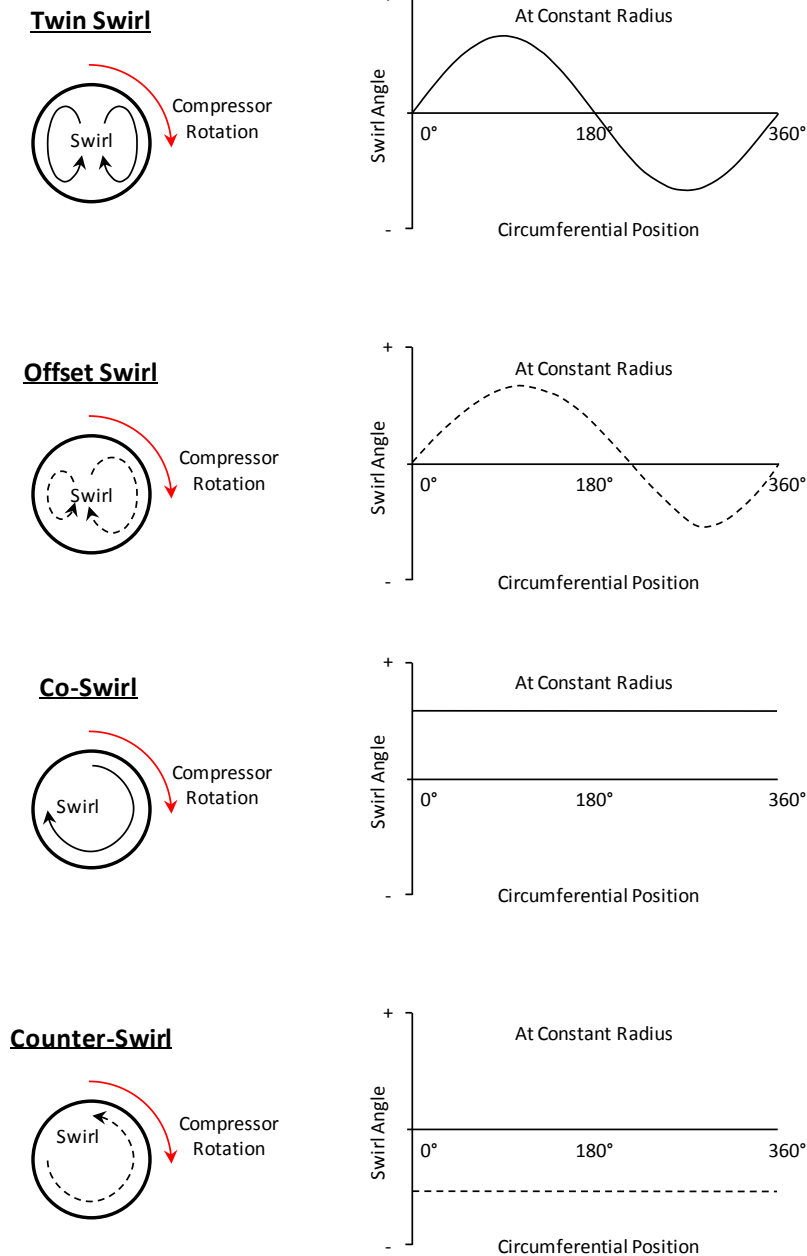


Figure 2. Swirl Pattern Definitions

One way to combat the effects of inlet swirl is the use of inlet guide vanes. Inlet guide vanes (IGVs) are used in many modern-day turbine engines to change the angle of the flow entering the compressor at the AIP. They are placed directly in front of the first rotor blade stage. IGVs are designed to add co-rotating swirl (swirl angle greater than zero) to the flow impinging on the rotor, which theoretically will move the compressor away from stall [3]. In the not-too-distant past it was not deemed necessary to simulate inlet swirl effects on turbine engines because of the relatively straight inlet systems found on most aircraft. Also, the development of IGVs for turbine engine designs was thought to negate the effects of swirl. However, many current and future military aircraft designs utilize S-shaped inlet ducts with sharp bends into the engine inlet systems for the sake of low observance and other stealth initiatives permeating the defense community. The S-shaped inlet ducts can produce swirl.

Investigations have been performed to characterize the effects that S-shaped ducts may have on the flow properties at the AIP of turbine engines [3]. It has been found that the swirl generated by the S-shaped duct can be severe enough to cause flow separation on the IGVs, which can cause an additional loss in engine stability margin. Although engines without IGVs are more sensitive to swirl at the AIP than those with IGVs, these studies showed that no engine is perfectly immune to the effects of inlet swirl. Several methods for simulating inlet swirl in turbine engine ground tests are currently under development at the Arnold Engineering Development Complex (AEDC) [4]. Evaluating the effect of inlet swirl on turbine engine compressor performance during ground tests,

coupled with targeted modeling and simulation techniques, would reveal engine performance and operability issues before initial flight testing.

1.3 PRESENTATION OF RESULTS

All results will be presented using a figure known as a fan/compressor map. Its use in the turbine engine community is widespread, and allows for a fairly simple depiction of fan/compressor performance and operability. A sample compressor map is given in Figure 3. The vertical axis is in terms of the total pressure ratio across the fan or compressor, while the horizontal axis is in terms of corrected (referred) mass flow. Lines of constant fan speed are plotted across the map, originating from a diagonal line known as the Operating Line, and terminating at the Stall/Surge Line. It is also common to display lines of efficiency on the same plot, but for the purpose of this investigation, that information is omitted.

All F109 technical data and related model predictions presented in this report have been normalized to protect the proprietary nature of the F109 engine and its performance characteristics. Fan map axis values are given as a percentage of an arbitrarily chosen value that is not reported in this document.

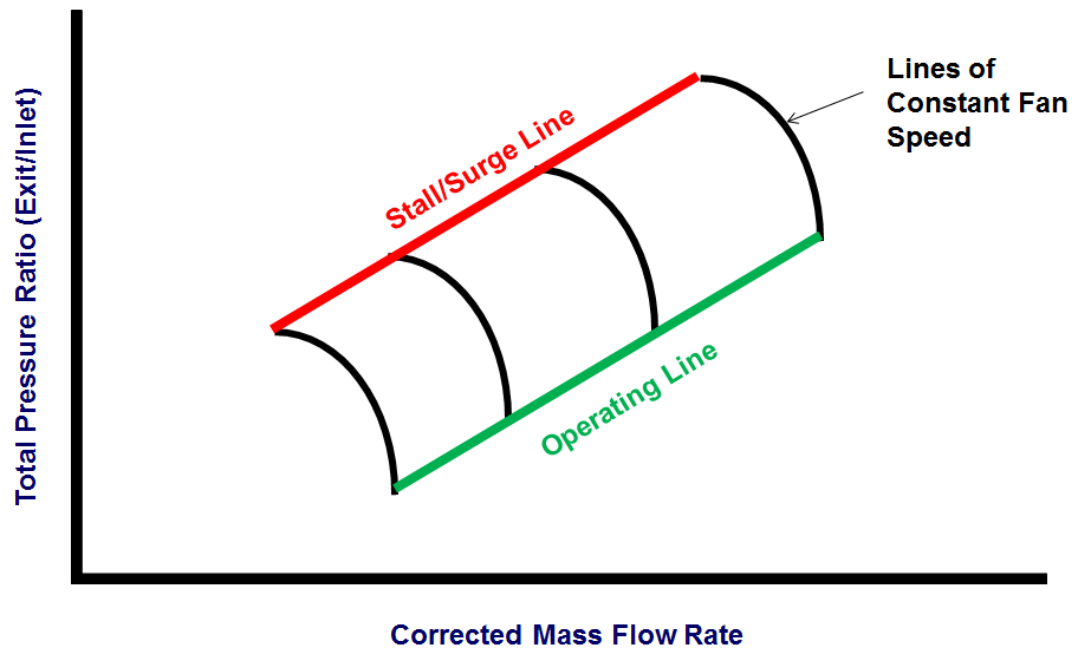


Figure 3. Sample Compressor Map

2.0 LITERATURE REVIEW

2.1 EFFECTS OF SWIRL ON ENGINE PERFORMANCE AND OPERABILITY

Modern military fighter aircraft are becoming more and more susceptible to the effects of inlet swirl due to the gravitation towards the use of S-shaped inlet ducting, however the problem is not entirely new. Legacy platforms such as the General Dynamics F-111 and Panavia Tornado experienced flight test interruptions due to complications from inlet swirl at extreme flight maneuvers. The Tornado encountered stall in both engines at several different flight conditions during developmental flight testing attributed to swirl introduced by the inlet duct [5]. As a result, extensive research was conducted to not only mitigate the effects of swirl, but to also produce ways to simulate the inlet swirl patterns more accurately during ground test. Aulehla offers, in Reference 5, a compilation of the main findings of these investigations, and was able to draw conclusions from those results. It was found that the inlets on most conventional supersonic fighter aircraft generate some sort of swirl. It was also found that bulk swirl created by the engine inlet could be eliminated by using intake fences. However, researchers noticed that the intake fences were less effective against paired swirl because of the unstable nature of paired swirl [5]. The Tornado experience proved that means for generating and predicting swirl during ground test were necessary for military engines both with and without inlet guide vanes.

Much work has been conducted at AEDC to address some of the problems magnified by the Tornado experience. As a premier turbine engine ground test facility, the need for quality swirl generation techniques has been realized. Beale, et. al. [6] detailed two types of swirl generators currently under development at AEDC. Concepts employing turning vanes are under investigation for generating bulk swirl and twin swirl, while a swirl chamber is under investigation for the generation of twin swirl [6]. Turning vanes resemble a set of inlet guide vanes and feature variable blade incidence angle and twist angle in order to provide remotely variable swirl angles at the face of the engine [6]. The swirl chamber operates in place of a bellmouth and forces the flow to enter the inlet duct tangentially so that an internal circumferential flow is established [6]. The swirl angle is changed by varying the entrance openings of the swirl chamber. Both concepts have been analyzed using computational fluid dynamics and functional prototypes are under development. The bulk and twin swirl generators used to produce the test data contained in this report are described briefly in Section 3.4.2.

Simultaneous to the development of the swirl generator concepts, a parallel effort to predict the effects of swirl computationally has been sought. Beale, et. al. [6] have used several numerical methods to predict the effects of inlet swirl on fan performance of an F109 turbofan engine. The three methods used were one-dimensional mean line analysis, parallel compressor analysis, and three-dimensional Euler analysis. The authors used the one-dimensional mean line analysis and the three-dimensional Euler analysis to predict the effects

of co- and counter- bulk swirl on fan performance. The authors used the results from the mean line analysis to develop scaling factors that were used in the parallel compressor analysis. The parallel compressor analysis was then used to evaluate the effects of co- and counter- bulk swirl as well as twin swirl on parallel compressor performance [6]. An extension of this work was provided by Fredrick [11], where the one-dimensional mean line code was integrated with the parallel compressor code to more efficiently predict inlet swirl.

2.2 INVESTIGATION OF STALL CRITERIA FOR SWIRL

An extensive search was conducted to find the most suitable stall criteria for inlet swirl model predictions. While the original DYNTTECC model used stage characteristic maps to determine compressor stall, recent work by Fredrick implemented a new stall determination technique provided by the embedded one-dimensional mean line code. Traditionally recognized in industry as the standard stall criteria, the diffusion factor was chosen as the method to determine stall in the modified DYNTTECC/MLC model. Realizing that there have been a host of stall criteria definitions theorized in the last half century, several methods were studied and evaluated for their usefulness under inlet swirl conditions.

2.2.1 DIFFUSION FACTOR

The principal reason for losses in the flow across axial flow compressor blade rows is due to the separation of the friction boundary layers on the suction surface of the blades. The most important development in assessing this blade

separation is the diffusion factor developed by Lieblein in 1953 [7]. Equation 1 is the most common form of Lieblein's diffusion factor, and is defined based on inlet and exit blade velocities, along with a given blade solidity (σ).

$$DF = 1 - \frac{V_{2R}}{V_{1R}} + \frac{|v_{1R} - v_{2R}|}{2\sigma V_{1R}} \quad (1)$$

There is a direct correlation between total pressure loss and blade diffusion (separation), which is measured by the diffusion factor. For diffusion factors above roughly 0.6, there is a steep rise in the total pressure loss, as shown in Figure 4. Because of this, the diffusion factor is generally found to be no more than 0.6 at stall condition [8]. DYNTTECC was originally modified to use rotor diffusion factor as the stalling criteria. The rotor diffusion factor is calculated by the 1-D mean line code and passed along to the main DYNTTECC routine.

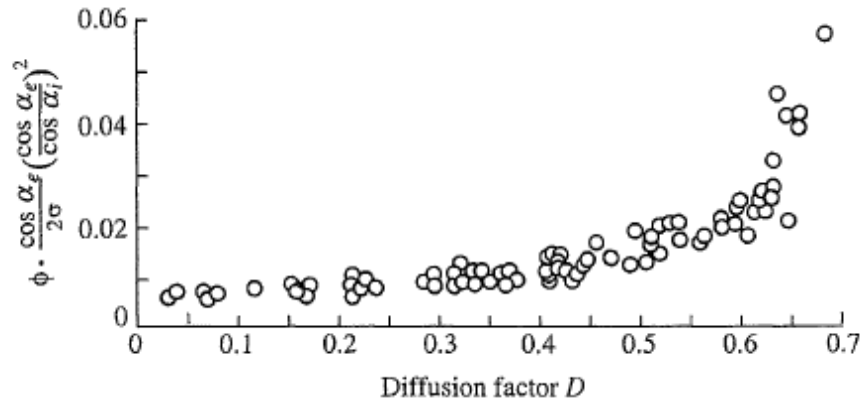


Figure 4. Diffusion Factor/Loss Relationship [8]

Schobeiri suggested that the traditional diffusion factor can and should be manipulated to include the effect of compressibility on the flow through the blades, and thus the diffusion factor [9]. Equation 2 is the expression derived by Schobeiri as an extension of Lieblein's groundbreaking work. The term in brackets, which is heavily influenced by the inlet relative Mach number, is simply multiplied by the final term of the original diffusion factor definition.

$$DF_m = 1 - \frac{V_{2R}}{V_{1R}} + \frac{|v_{1R} - v_{2R}|}{2\sigma V_{1R}} \quad (2)$$

$$* \left[1 - \frac{V_{1A} \sin\beta_1}{V_{2A} \sin\beta_2} M_{1R}^2 \left(\frac{V_{1A} \sin\beta_1}{V_{2A} \sin\beta_2} - 1 \right) \right]$$

A final modification to the traditional diffusion factor can be made to account for the dynamic nature of compressor performance at and near stall. While DYNTECC typically uses steady state characteristic maps to solve the governing equations (see Section 3.1), Reference 10 provides a discussion of techniques available for modeling the highly dynamic compressor characteristics near stall. For a dynamic event such as rotating stall or surge, the use of time-averaged steady state characteristics is not necessarily correct. In the rotating stall region, rotating stall develops very rapidly and the globally steady characteristic is no longer applicable [10]. To provide a dynamic approximation of stall, a first order time lag on the diffusion factor can be incorporated into the modeling technique in the rotating stall region. The first order lag equation used is given in Equation 3.

$$\tau \frac{\partial DF}{\partial t} + DF = DF_{ss} \quad (3)$$

The time constant, tau (τ), essentially allows for the delay of stall determination to offset any error incurred by the use of time-averaged steady state stage characteristics. For the purpose of this investigation, tau was arbitrarily chosen so that the model predicted stalling diffusion factor at clean inlet conditions would allow the model to reach the clean inlet data stall limit. Nevertheless, this first order lag equation can only at best delay stall compared to the steady state approximation, limiting its usefulness in this particular inlet swirl investigation due to the mix of over- and under-prediction of stall relative to test data using the model created by Fredrick [11].

2.2.2 DIFFUSION RATIO

Several years after developing the diffusion factor, Lieblein published his follow-on work that described another method of correlating blade performance to blade loss and separation. The diffusion ratio, which is the ratio of peak blade exit velocity to the mean blade exit velocity, is a natural extension of the diffusion factor. Lieblein found that this new diffusion ratio correlated well with his earlier stall prediction technique at incidence angles above the minimum loss condition [12]. The standard diffusion ratio at stall is given by Equation 4. This equation is empirical in nature, and was derived from extensive cascade testing of 65-series and C.4 circular arc blade shapes [12]. Theoretically, this expression should

have a greater influence of swirl angle resulting from the introduction of inlet and outlet flow directions at stall (β), as well as the change in incidence angle (i).

$$DR = \frac{\cos\beta_2}{\cos\beta_1} \left[1.12 + 0.007(i - i_{op})^{1.43} + 0.61 \frac{\cos^2\beta_1}{\sigma} (\tan\beta_1 - \tan\beta_2) \right] \quad (4)$$

Much like the diffusion factor, there is a direct correlation between total pressure loss and blade diffusion (separation), which is also measured by the diffusion ratio. For diffusion ratios above roughly 2.0, there is a steep rise in the momentum thickness, as shown in Figure 5. An increase in momentum thickness can correspond to an increase in blade separation, leading to higher losses across the blade. Because of this, the diffusion ratio is generally found to be no more than 2.0 at stall condition [8].

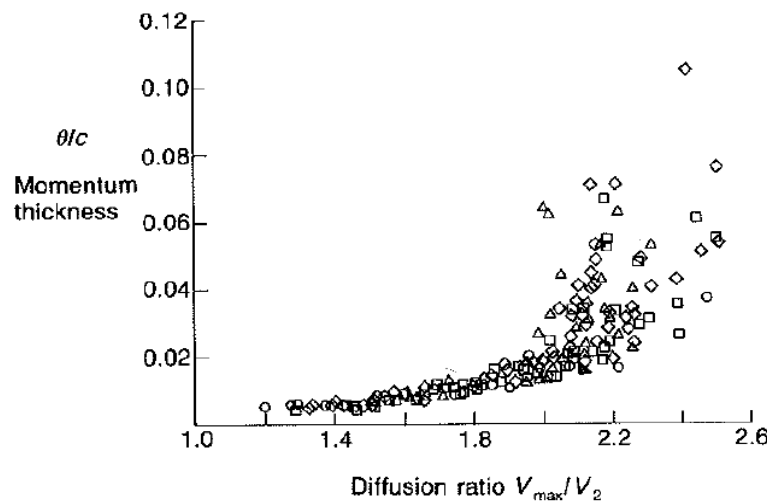


Figure 5. Diffusion Ratio/Momentum Thickness Relationship [8]

In the same 1957 report, Lieblein also offered an alternate definition of the standard diffusion ratio that can be used if given an alternate set of known inputs. The previous diffusion ratio expression is only valid if the inlet and outlet flow angles at stall are known. However, if the relative flow angles are known only at the minimum loss condition, a new expression would be necessary [12]. The diffusion ratio calculation given in Equation 5 differs from the previous in that the inlet and outlet relative flow angles are expressed in terms of the minimum loss condition, which, for the purposes of this investigation, is assumed to be found at the operating line. Nonetheless, the change in incidence angle at stall will still need to be gathered.

$$DR_{op} = \frac{\cos[\beta_{2op} - 0.975(i - i_{op})]}{\cos\beta_{1op}} \left[1.12 + 0.007(i - i_{op})^{1.43} + 0.61 \frac{\cos^2\beta_{1op}}{\sigma} (\tan\beta_{1op} - \tan[\beta_{2op} - 0.975(i - i_{op})]) \right] \quad (5)$$

2.2.3 STATIC PRESSURE RISE COEFFICIENT

It was recognized by Koch and Smith that compressor stall was dependent on end-wall effects (clearances) and blade aspect ratio, which the

traditional diffusion factor does not take into account. The static pressure rise coefficient was developed to account for these shortcomings of the standard diffusion factor and ratio [13]. A host of empirically developed modifications can be applied to this equation that take into account Reynolds number, tip clearances, and axial blade spacing. These modifications are explained in depth in Reference 13. The simplified version of the static pressure rise coefficient is given in Equation 6.

$$C_p = \frac{c_p T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] - \frac{(U_2^2 - U_1^2)}{2}}{\frac{(V_{1R}^2 - V_2^2)}{2}} \quad (6)$$

2.2.4 De HALLER NUMBER

De Haller brought a simplified approach to the discussion of blade diffusion. He noted that the primary purpose of any compressor stage is to diffuse the fluid, leading to an increase in static pressure. The more the fluid is decelerated, the larger the pressure rise, leading to potential flow separation and stall [8]. The most basic of the blade stall correlations, the de Haller number (Equation 7) is the overall deceleration (diffusion) ratio across the rotor in terms of relative velocity. The de Haller number is generally found to be no less than 0.72 at stall condition.

$$DH = \frac{V_{2R}}{V_{1R}} \quad (7)$$

2.3 CONCLUSIONS FROM LITERATURE REVIEW

Turbine engine inlet integration issues brought on by inlet swirl distortion have plagued the developmental community for decades, with no signs of easing in the coming years. Several military fighter aircraft programs, such as the Tornado, have struggled with simulating and quantifying the effects of inlet swirl, and future programs will have to address the issue due to the advent of the S-shaped inlet. AEDC is at the forefront of the turbine engine testing community, and extensive work has been conducted to develop vital tools that will aid in the understanding of inlet swirl effects on engine performance. Swirl generators are under development and are poised to be an instrumental player in the turbine engine ground test process. In addition, computational tools to predict and evaluate the effects of inlet swirl are continuing to improve in terms of efficiency and accuracy.

2.4 PROBLEM STATEMENT

The goal of the work reported herein was to modify the combined DYNTTECC/MLC developed by Fredrick so that the model predictions generated for inlet swirl compared more favorably with acquired test data. Efforts to correct

this problem include calibrating to the clean inlet test data and investigating the stall determination technique. The modified DYNTTECC/MLC is to be used to analyze the effects of different types of bulk and paired swirl on F109 fan performance and operability with improved accuracy.

3.0 BACKGROUND

3.1 DYNTECC/PARALLEL COMPRESSOR THEORY

One type of compressor model commonly used to investigate inlet distortion is called a parallel compressor model. Parallel compressor models divide the compressor control volumes into parallel or circumferential segments that can be specified to have separate inlet boundary conditions [14]. Despite the distinct inlet boundary conditions, each segment will arrive at the same exit boundary condition, and an illustration of this concept can be found in Figure 6.

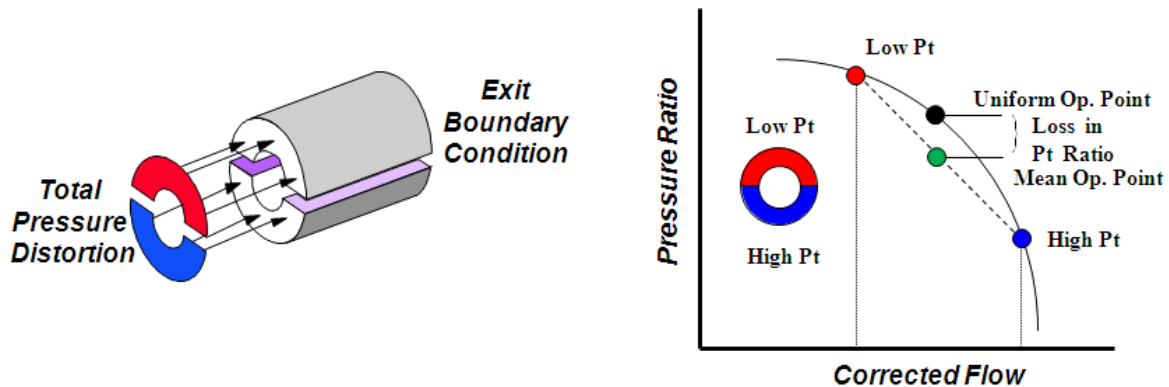


Figure 6. Parallel Compressor Theory

DYNTECC (Dynamic Turbine Engine Compressor Code) is a one-dimensional model that utilizes the parallel compressor theory to investigate the effect of inlet distortion on the compression system stability limit [15]. Each compression stage is divided into elemental control volumes, allowing DYNTECC to model the test article on a stage by stage basis. Inlet and exit boundary

conditions of the overall compression system are input to DYNTECC by the user, and both static pressure and Mach number can be used as the specified exit boundary condition. Quasi one-dimensional mass, momentum, and energy conservation equations are solved using a finite difference numerical technique at each stage or elemental control volume. The control volume concept used by DYNTECC is depicted in Figure 7. Source terms are supplied by stage pressure and temperature characteristic maps, and are used to provide closure for the momentum and energy equations with stage forces and shaft work values [15].

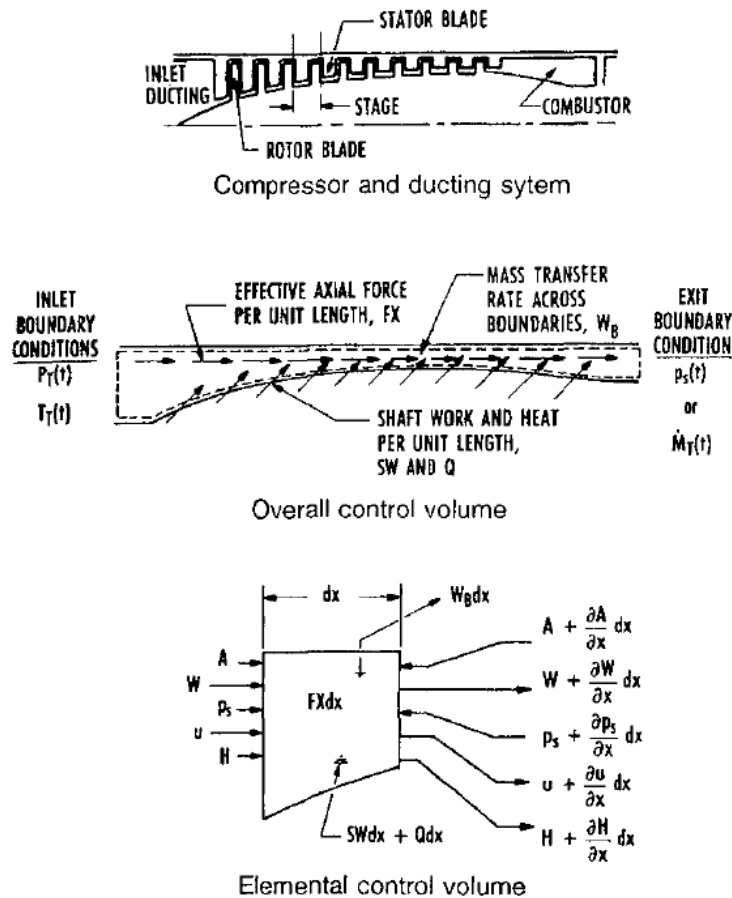


Figure 7. DYNTECC Control Volume Concept [15]

The foundation of DYNTECC is built upon the one dimensional forms of the mass, momentum, and energy conservation equations. The one dimensional conservation of mass expression used by DYNTECC is given in Equation 8, where ' W_B ' is the inter-stage bleed flow per distributed length, ' W ' is the mass flow rate, ' ρ ' is the density, and ' A ' is the area [15].

$$\frac{\partial(\rho A)}{\partial t} = -\frac{\partial W}{\partial X} - W_B \quad (8)$$

The one dimensional conservation of momentum expression used by DYNTECC is given in Equation 9, while the contained momentum impulse term and axial force term are given in Equations 10 and 11 respectively. The axial velocity is denoted by ' u ', ' P_s ' is the static pressure, and ' F_b ' is the blade force [15].

$$\frac{\partial W}{\partial t} = -\frac{\partial(IMP)}{\partial X} + F_x \quad (9)$$

$$IMP = W * u + P_s * A \quad (10)$$

$$F_x = F_b + \frac{\partial(A)}{\partial X} \quad (11)$$

The one dimensional conservation of energy expression used by DYNTECC is given in Equation 12, while the contained energy function is given

in Equation 13. The rate of shaft work is denoted by 'SW', 'Q' is the rate of heat addition to the control volume, 'H_B' is the total enthalpy of the bleed flow, and 'e' is the internal energy [15].

$$\frac{\partial(EA)}{\partial t} = -\frac{\partial H}{\partial X} - H_B + SW + Q \quad (12)$$

$$E = \rho^* \left| e + \frac{u^2}{2} \right| \quad (13)$$

Despite a host of user specified inputs provided at the onset of each DYNTECC solution, there are still five unknowns contained in the three conservation equations. During normal operation, DYNTECC uses the steady state stage characteristic maps to obtain stage pressure ratio (PR) and temperature ratio (TR) values which provide closure for the conservation equations. DYNTECC then backs out steady state values for the axial stage forces (F_x) and rate of shaft work (SW) using equations 7 and 10, thus leaving three unknowns and three equations, which can be easily solved. It is worthy to note that this process is only useful for pre-stall operation, and is inaccurate for post-stall operation [10].

DYNTECC was originally developed to only model inlet total pressure and temperature distortion phenomena. During normal operation where only the distortion pattern is altered, DYNTECC can apply the same set of stage

characteristic maps for all cases since the stage characteristic does not change with inlet total pressure or temperature. However, the introduction of swirl will change the incidence angle of the rotor blades, which consequently greatly alters the clean inlet stage characteristics. In order to use DYNTTECC to model swirl, stage characteristic maps have to be developed for each individual swirl case, which can prove to be tedious. An alternate solution was needed to more efficiently model inlet swirl effects, and the one-dimensional mean line code was chosen to streamline the process [11].

3.2 MEAN LINE THEORY

Instead of developing unique compressor characteristic maps in DYNTTECC for each individual inlet swirl case, it would be desirable to develop the source terms for closure in the DYNTTECC solver by an alternate function within the parallel compressor code. The function chosen was a one-dimensional mean line code that had been used for decades as a standalone product. In 2003, Grady Tibboel integrated a one-dimensional compressor stage characteristics mean line code into a parallel compressor code called DYNTTECC [16], and Nick Fredrick applied this modified model to the investigation of inlet swirl in 2010 [11].

The mean line code is a compressible, one-dimensional, steady-state compressor model that simulates each blade row's performance. The code uses velocity diagrams, blade relative total pressure loss correlations, and blade exit deviation correlations to develop individual stage characteristics. Like

DYNTECC, detailed blade geometry is not required. The mean line code has four modes of operation, three of which use a Newton multi-variable method to converge on a solution while the fourth method calculates the solution directly based on inlet flow conditions, relative total pressure loss across the rotor blade, and exit angle deviation [17].

The inlet total pressure, total temperature, Mach number, and swirl angle are specified by the user. Inlet static pressure, static temperature, and the speed of sound can be calculated using the user supplied values along with the isentropic relations. Velocity triangles, like those shown in Figure 8, are used by the mean line code to determine the inlet relative velocity, inlet relative flow angle, and inlet relative Mach number. Isentropic relationships are then used to calculate the inlet relative total pressure and relative total temperature. In order to calculate the total pressure and temperature across the rotor, the relative mass flow function (MFF), relative total temperature ratio, relative total pressure ratio, and ratio of areas perpendicular to the flow must then be calculated [17]. A detailed explanation of this process can be found in Reference 17.

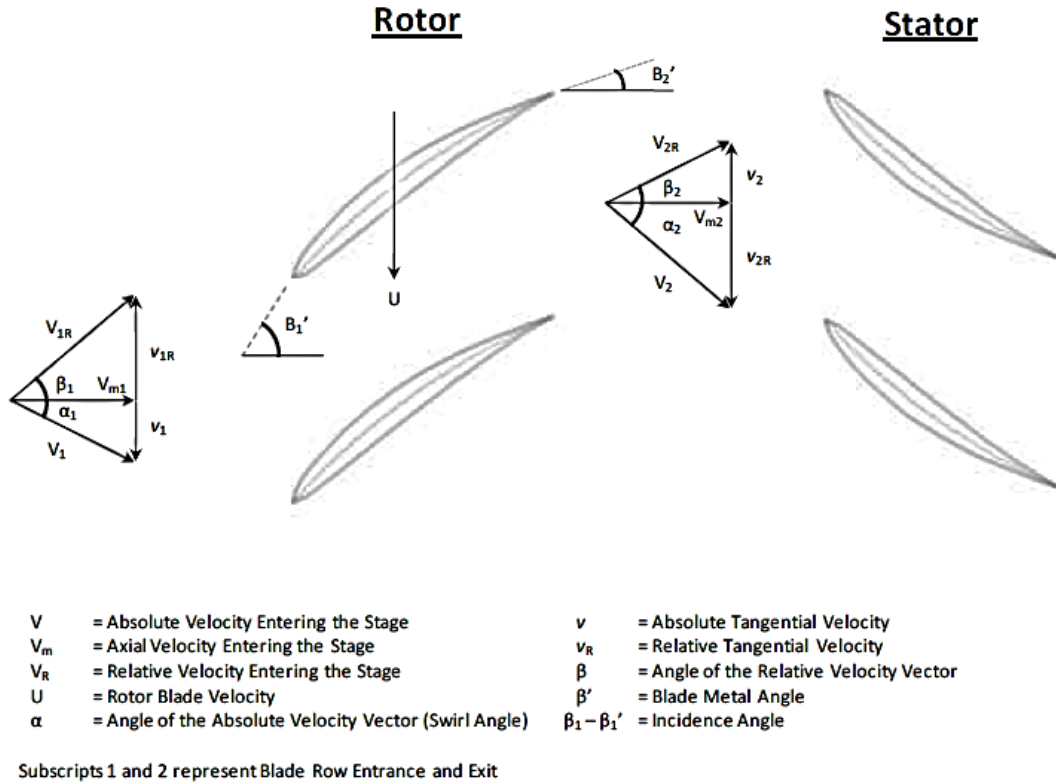


Figure 8. Axial Compressor Velocity Triangle [11]

During normal operation, the relative total pressure loss and exit deviation angle of the blade are calculated from open source empirical correlations internal to the code. In addition, experimental data can be used to calibrate the blade relative total pressure loss and exit deviation angle resulting in add-loss and add-deviation maps. Using these values for loss and deviation, along with the inlet flow conditions, allow for the determination of each stage characteristic for a given solution. The ability to by-pass the correlations and look up the blade relative total pressure loss and exit deviation angle directly from two-dimensional tables was added by Fredrick [11].

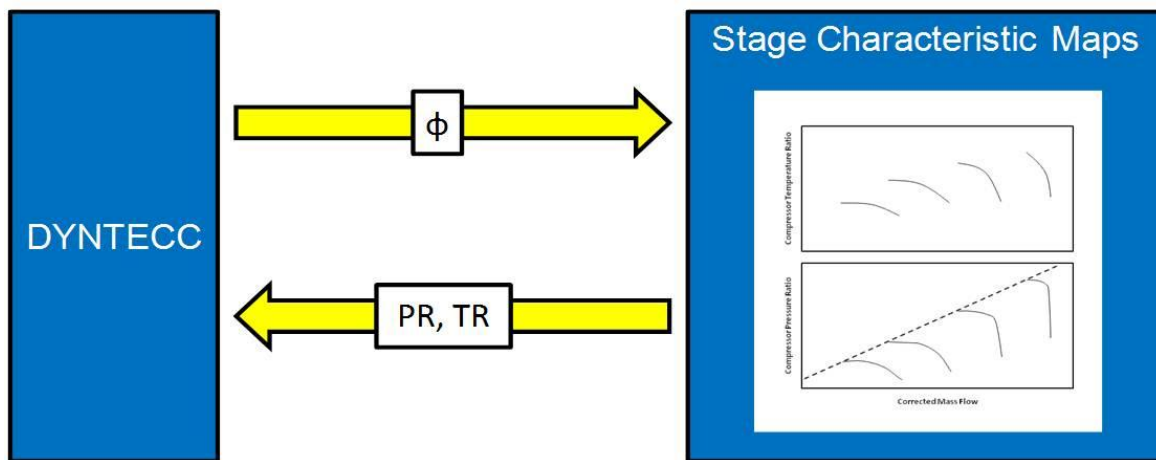
Once integrated with DYNTECC, the mean line code can provide “real time” source terms such as stage pressure and temperature ratio at a specified operating condition. Instead of developing multiple maps for each individual swirl case, DYNTECC can now call on the mean line code to determine the source terms for any input swirl angle, inlet total pressure, or inlet total temperature. DYNTECC passes total pressure, total temperature, Mach number, mass flow, rotor speed, inlet and exit areas, and compressor exit static pressure to the mean line code. The mean line code is then able to determine the loss and deviation and calculate the stage pressure ratio and temperature ratio. The calculation of the pressure ratio and temperature ratio in the mean line code replaces the interpolation of pressure ratio and temperature ratio maps found in the original version of DYNTECC [11].

3.3 PREVIOUS M&S INVESTIGATION

The work presented in this report is a direct extension of the work performed by Nick Fredrick in 2010 [11]. A new version of the MLC was incorporated into the parallel compressor model DYNTECC as a subroutine. As a result, DYNTECC was able to use the MLC to calculate a point-by-point representation of the stage characteristics internally without the use of temperature and pressure characteristic maps, which was integral to the original version of DYNTECC. Traditionally, DYNTECC would call upon a series of temperature and pressure maps for each stage in order to generate total compression system pressure and temperature ratios. The modified

DYNTECC/MLC approach now sends several inputs and parameters to the internal mean line routine to generate pressure and temperature ratios for each blade row, as well as a stall determination factor [11]. This modification to DYNTECC is outlined in Figure 9.

Normal DYNTECC Method



Modified DYNTECC Method

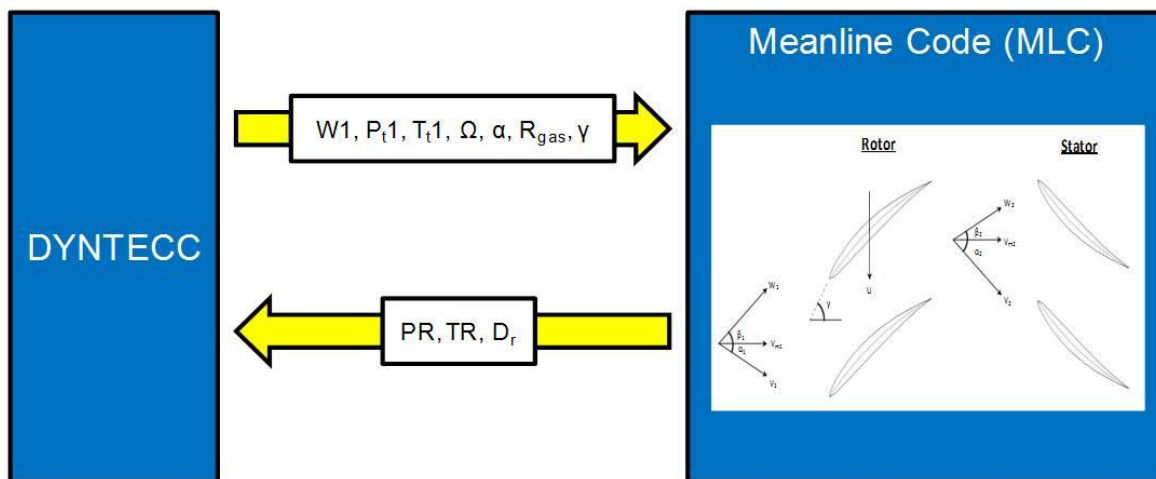


Figure 9. Modified DYNTECC Approach

During normal operation employing stage characteristic maps, DYNTECC analyzes the slope of stage characteristic map lines to determine when stall occurs. Both DYNTECC and the MLC were modified to determine stage stall without the use of the characteristic maps. 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. Historical sources show that the rotor diffusion factor should be no more than 0.6 at stall. Frederick calibrated the value used as the stalling diffusion factor by analyzing available clean inlet F109 fan map data and the mean line code. The value varied across the fan speeds analyzed, so the average was taken of all the stalling diffusion factors. A value of 0.555 was used for all subsequent swirl model runs [11]. This value was chosen as a matter of convenience by Fredrick, and was deemed sufficient for the investigation at the time. A plot of the F109 fan map generated diffusion factor values as a function of fan speed is shown in Figure 10.

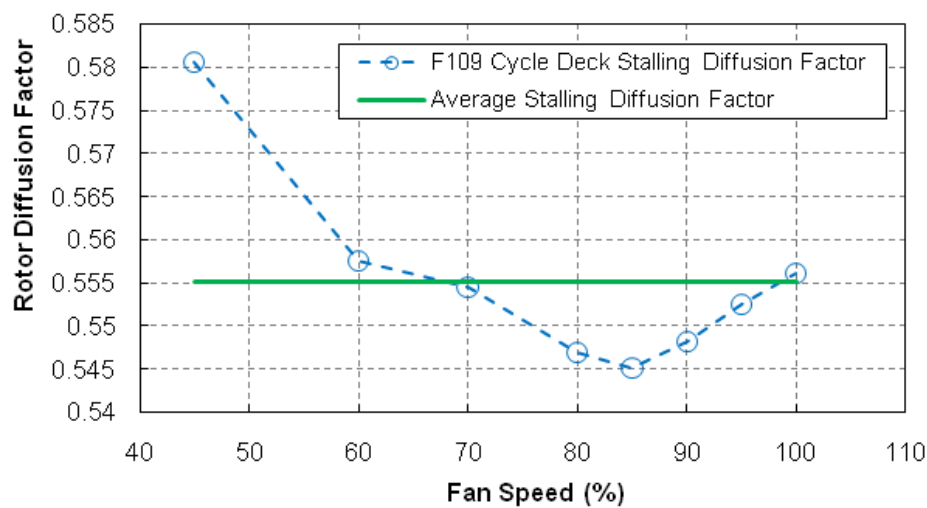


Figure 10. Average Stalling Diffusion Factor [11]

Additional modifications were made to the MLC in order to by-pass blade relative total pressure loss and deviation correlations and look up those values directly from a user provided two-dimensional table. Stage characteristics required for developing the relative total pressure loss and blade exit deviation tables were obtained from the F109 cycle deck [11]. The F109 cycle deck was run for several mass flow points along each speed line from 20% to 115% fan speed to develop the loss and deviation look-up maps. 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. Using the data generated from running the mean line code at all cycle deck points shown in Figure 11, two-dimensional loss and deviation maps were produced for both the rotor and stator [11]. The rotor specific maps are shown in Figure 12. Note that the color gradients in the figure reflect the change in total pressure loss and exit deviation as specified in the scales adjacent to each plot.

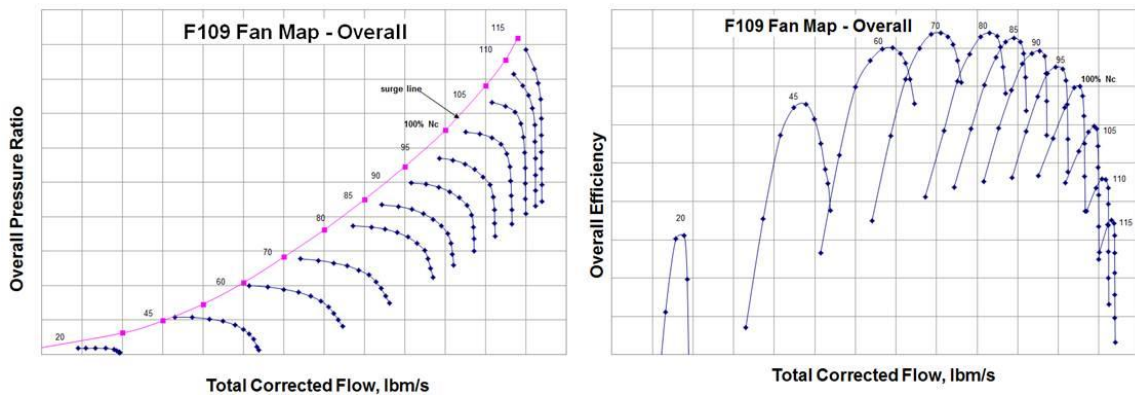


Figure 11. F109 Normalized Fan Map [11]

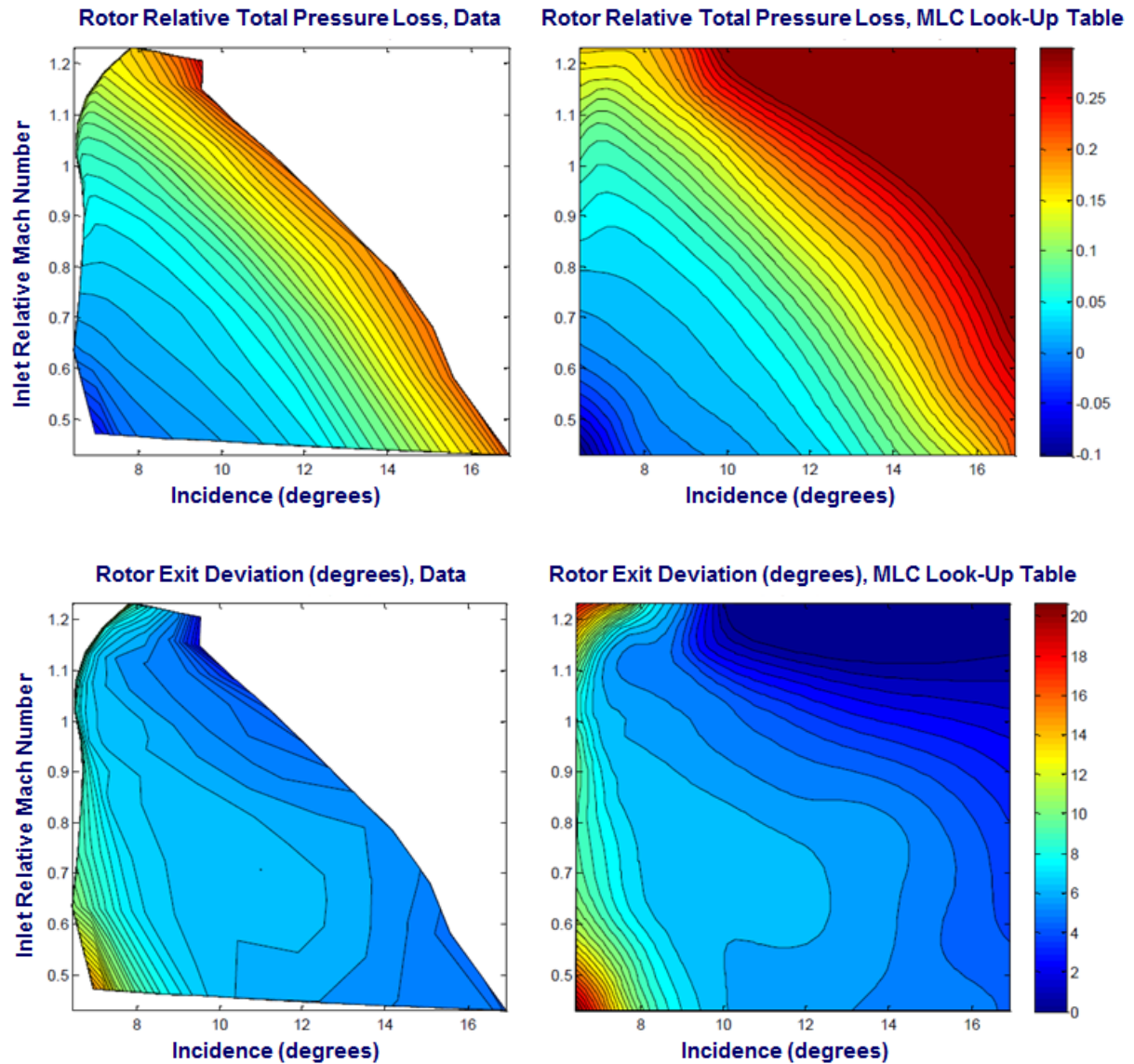


Figure 12. F109 Loss and Deviation Maps [11]

The combined DYNTTECC/MLC model was validated by comparing clean inlet predictions to the F109 cycle deck as well as clean inlet data obtained at the USAFA. The DYNTTECC/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, as seen in Figure 13 and Figure 14 [11].

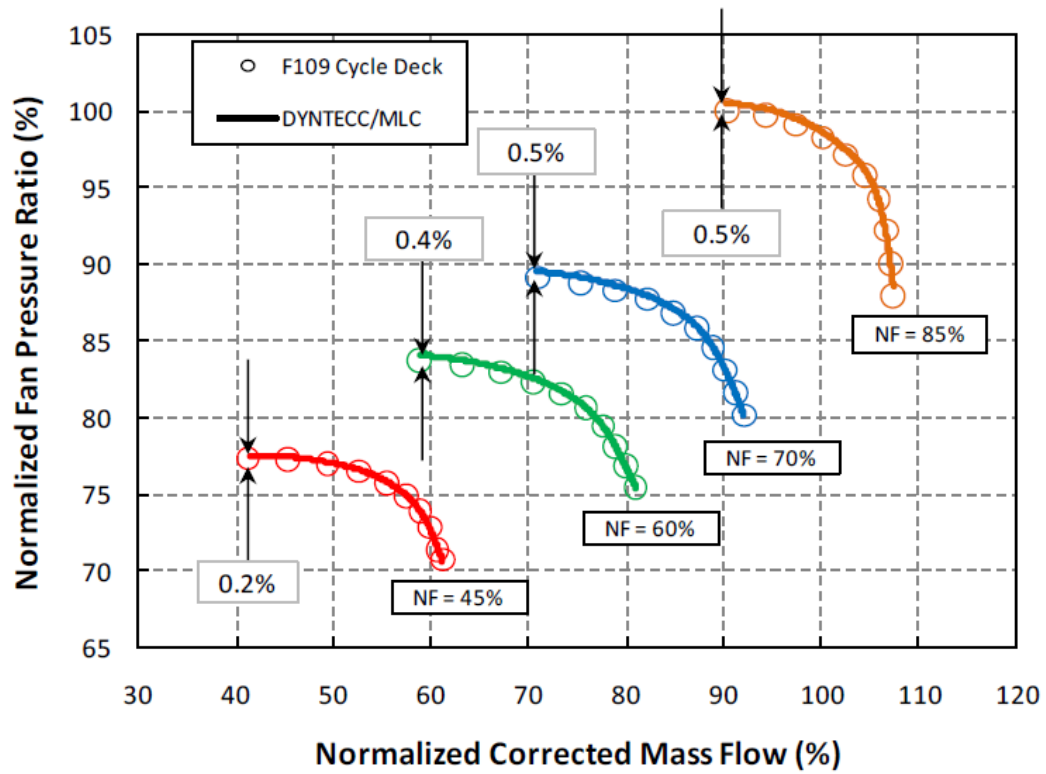


Figure 13. Cycle Deck Clean Inlet Model Validation, Normalized [11]

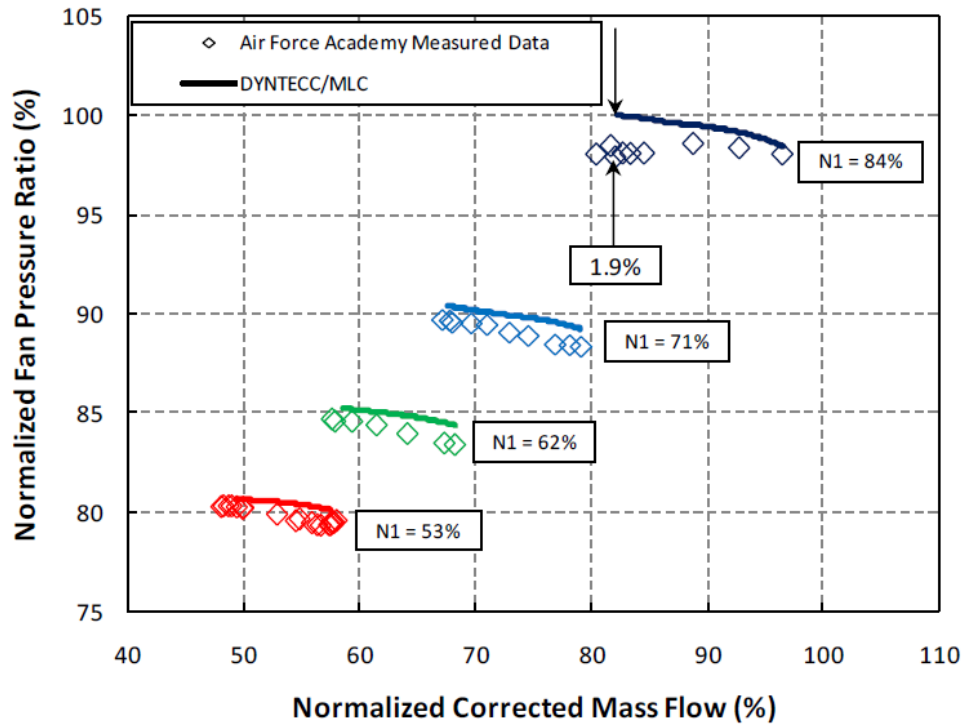


Figure 14. USAFA Data Clean Inlet Model Validation, Normalized [11]

The DYNTECC/MLC predicted clean inlet stall line 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 as reported in Reference 11. 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 was 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 [11]. This is depicted in Figure 15.

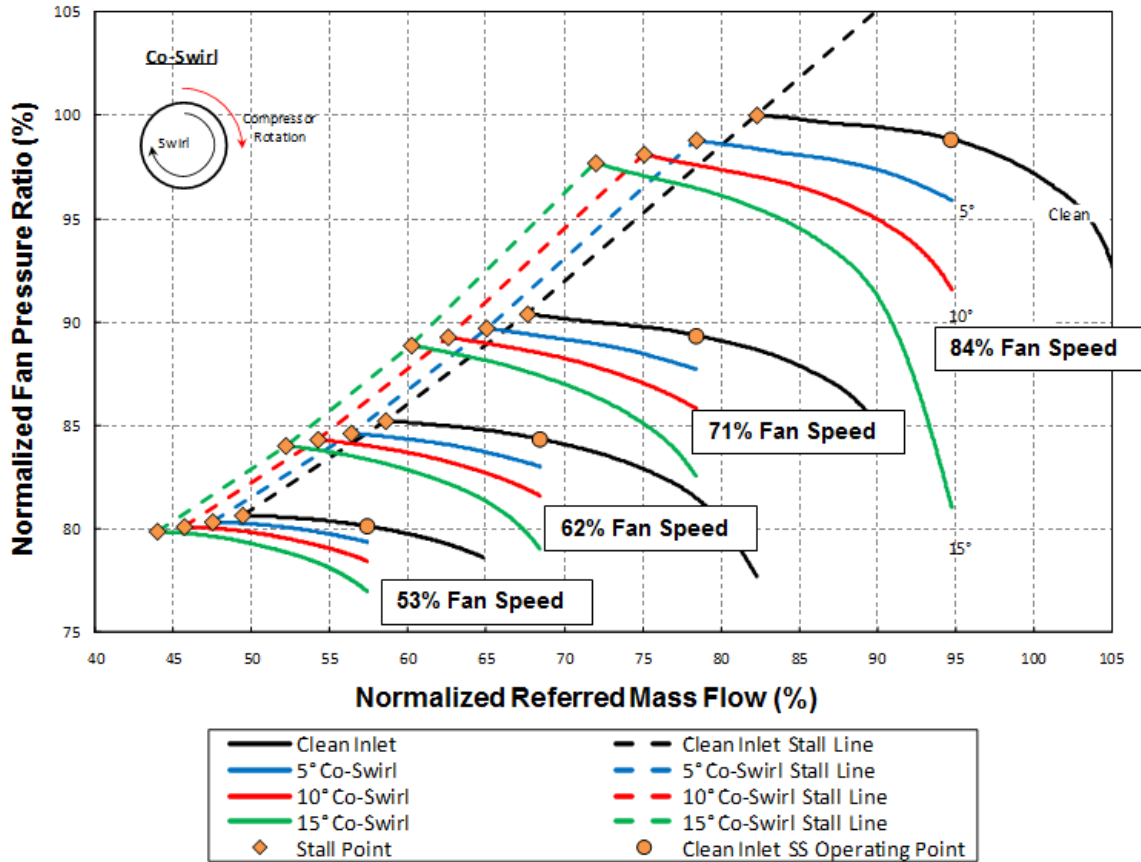


Figure 15. Normalized Co-Swirl Initial Predictions [11]

In the case of counter-swirl, DYNTECC/MLC model predictions showed the opposite. As counter-swirl intensity increases, Fredrick predicted that fan pressure ratio will increase while fan stability margin decreases [11]. This is depicted in Figure 16.

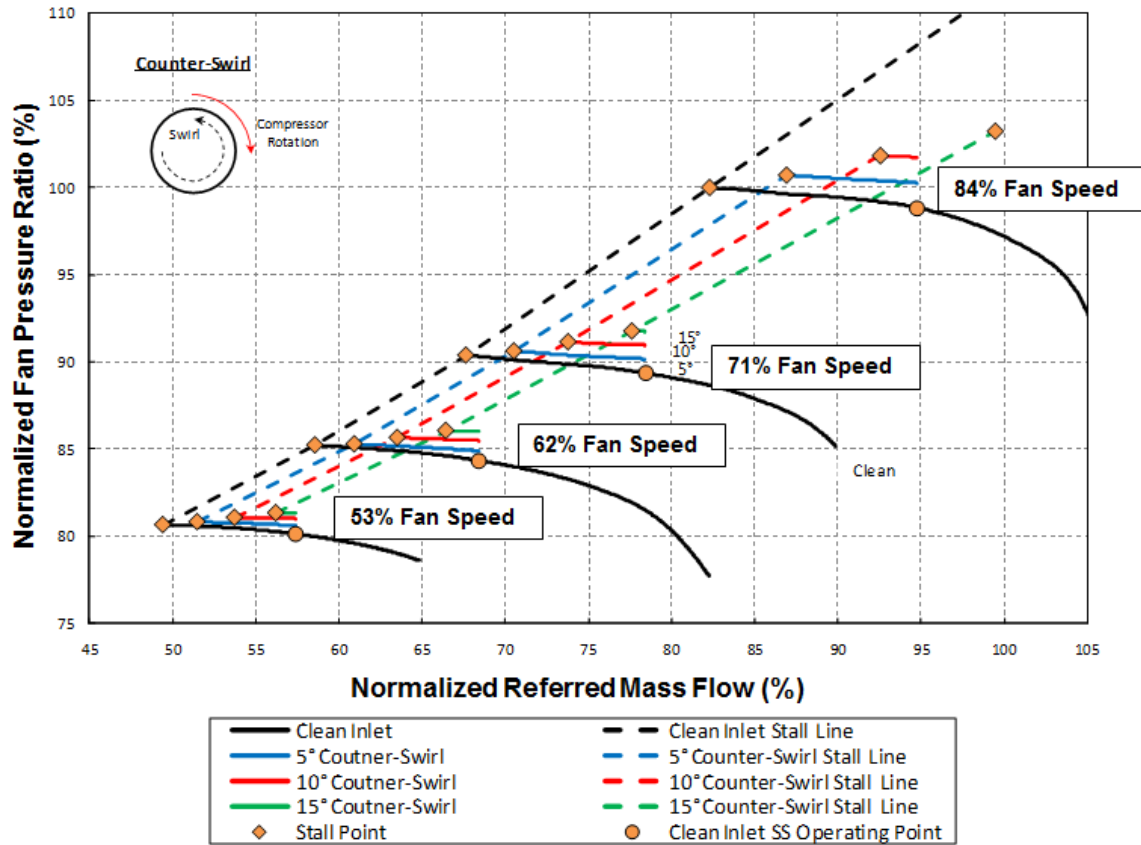


Figure 16. Normalized Counter-Swirl Initial Predictions [11]

Twin swirl was the only case of paired swirl modeled using DYNTTECC/MLC. Fredrick predicted that twin swirl reduces fan pressure ratio and also reduces fan stability margin. Fredrick showed the loss in stability pressure ratio with 10° twin swirl compared to the loss in stability pressure ratio with 10° counter- and co-swirl. For the same swirl angle, the loss in stability pressure ratio was much greater and increased at a higher rate with paired twin-swirl compared to bulk counter-swirl [11]. The twin swirl predictions for 53% and 71% fan speed are given in Figure 17 and Figure 18, respectively.

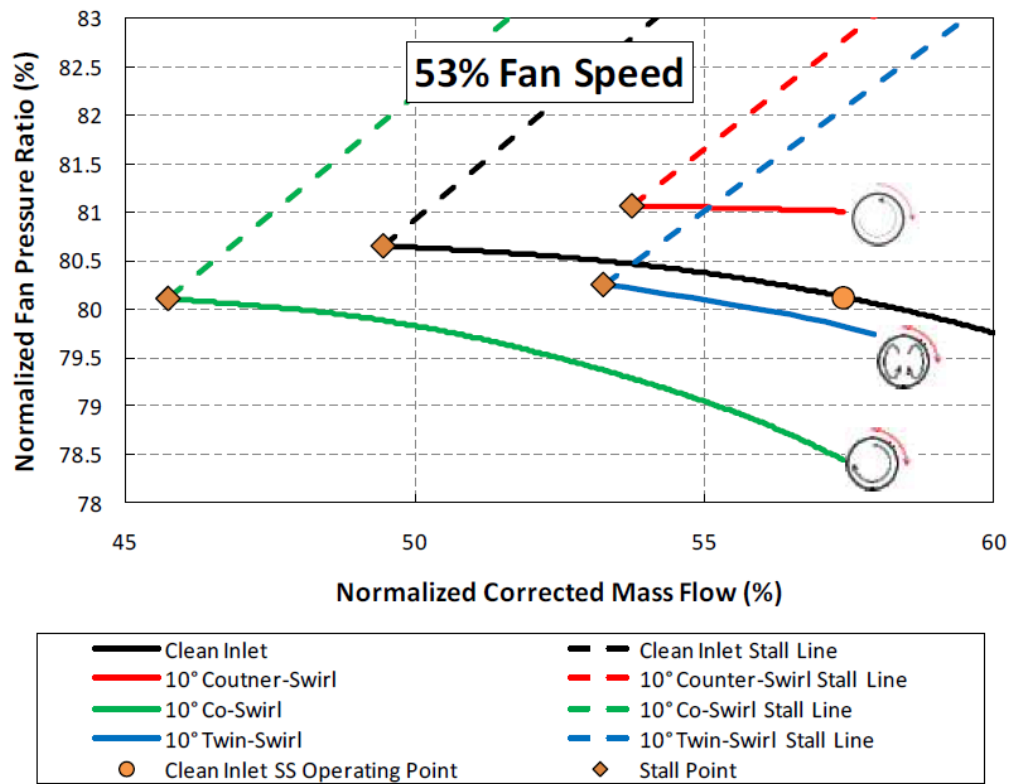


Figure 17. Normalized 53% Twin Swirl Initial Predictions [11]

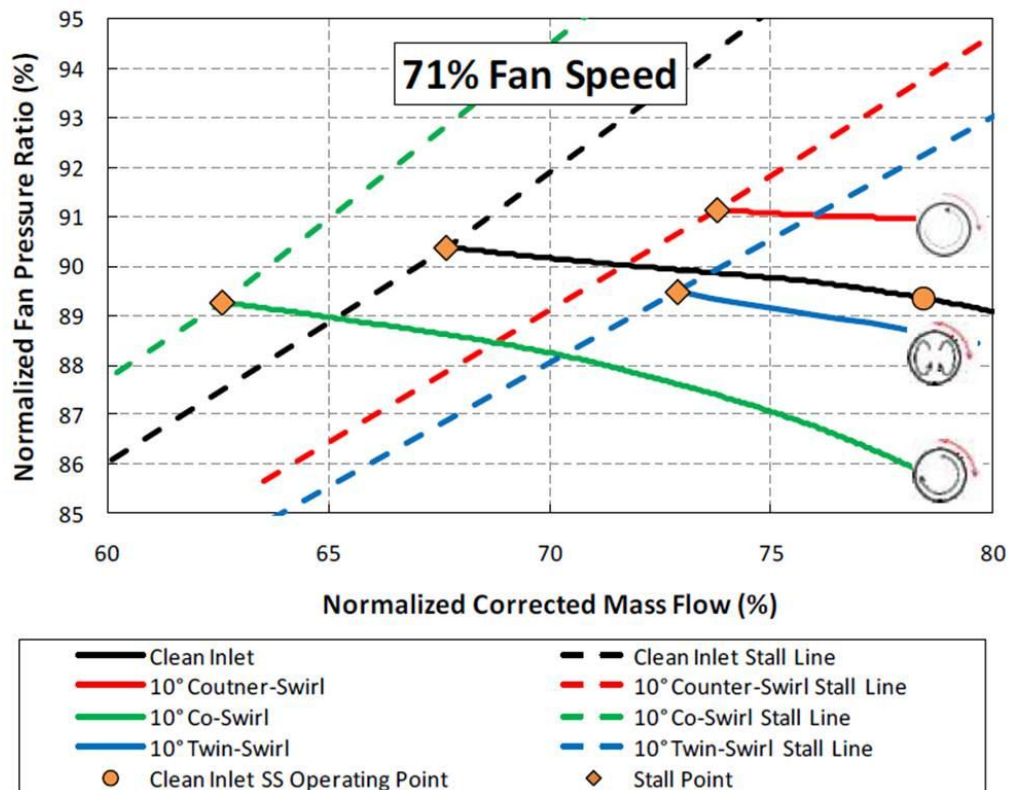


Figure 18. Normalized 71% Twin Swirl Initial Predictions [11]

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 line 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 had yet been gathered for the F109 with inlet swirl at the time of Fredrick's 2010 work.

3.4 F109 TURBOFAN ENGINE

3.4.1 ENGINE HISTORY

The Honeywell F109, shown in Figure 19, is a high by-pass ratio turbofan engine with a maximum thrust of 1330 pounds-force at sea level static, standard day conditions. The F109 has a single stage axial fan, a two stage centrifugal high pressure compressor, a reverse flow annular combustor, a two stage axial high pressure turbine, and a two stage axial low pressure turbine. The F109 has a bypass ratio of 5 to 1 and the by-pass flow mixes with the core flow before exiting through a common nozzle [6]. The F109 is ideal for inlet swirl testing because the fan is not equipped with IGVs, which will make it more sensitive to the presence of swirl. Universities like the USAFA and Virginia Polytechnic Institute and State University (Virginia Tech) presently use the F109 for various research endeavors [11].

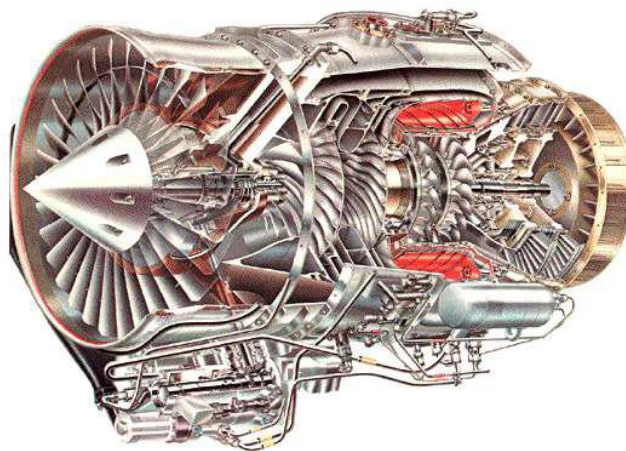


Figure 19. F109 Turbofan Engine [6]

3.4.2 USAFA SWIRL INVESTIGATIONS

F109 tests with AEDC-supplied swirl generators were conducted at the United States Air Force Academy in August 2011. The test was directed by AEDC personnel and conducted by USAFA faculty and students with instrumentation and test assets owned by the university. Data were collected in the following fashion: For each swirl condition, the specified swirl angle was set by a prearranged vane slot setting and manually measured flap setting. A flow angularity probe was not used for mapping of the fan. A previous wind-tunnel test without an engine was conducted to verify the flow angularity of the prearranged slot and flap settings using a 6-sided cobra probe.

When F109 testing was initiated, a slow transient along the operation line was made during accelerations/decelerations from idle to maximum speed and back again to verify nominal operation. Measurement of the individual speed line points was made possible by using an exhaust flow plug to backpressure the fan as shown in Figure 20. Steady-state data points were gathered at the start, while transient data points were initiated as the fan stall point approached. This entire process was then repeated for the baseline configurations. The configurations where data were taken, denoted by 'X', can be seen in Table 1 below.

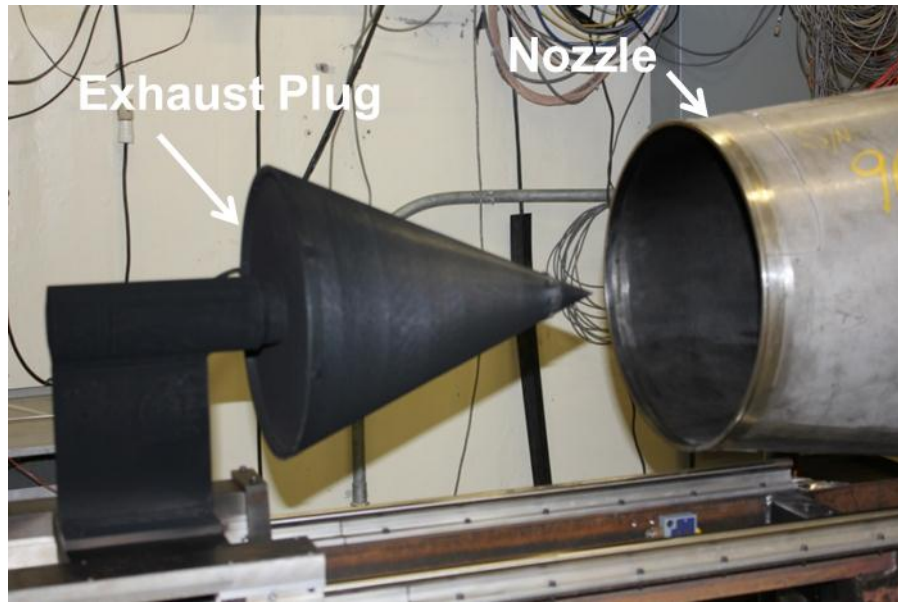


Figure 20. F109 Nozzle Flow Plug

Table 1. USAFA Test Configurations

Swirl Configuration	Op Line	53% N1	62% N1	71% N1	75% N1
Twin Swirl (+5/-5 Deg)	X	X	X	X	X
Twin Swirl (+9/-9 Deg)	X	X	X	X	X
Twin Swirl (+18/-18 Deg)	X	X	X	X	X
Bulk Swirl (+7 Deg)	X				
Bulk Swirl (-7 Deg)	X				
Bulk Swirl (+10 Deg)	X	X		X	
Bulk Swirl (+14 Deg)	X	X		X	
Bulk Swirl (-14 Deg)	X	X		X	

Two distinct AEDC-supplied swirl generators were used on this particular test: the Bulk Swirl Generator and Twin Swirl Generator. These swirl generators were designed by Dave Beale and are currently in the development and testing phase. This was the first test where these generators were placed in front of a live engine for purposes of investigating inlet swirl effects. Figure 21 provides an overall, as well as downstream, view of each generator installed at the United States Air Force Academy.

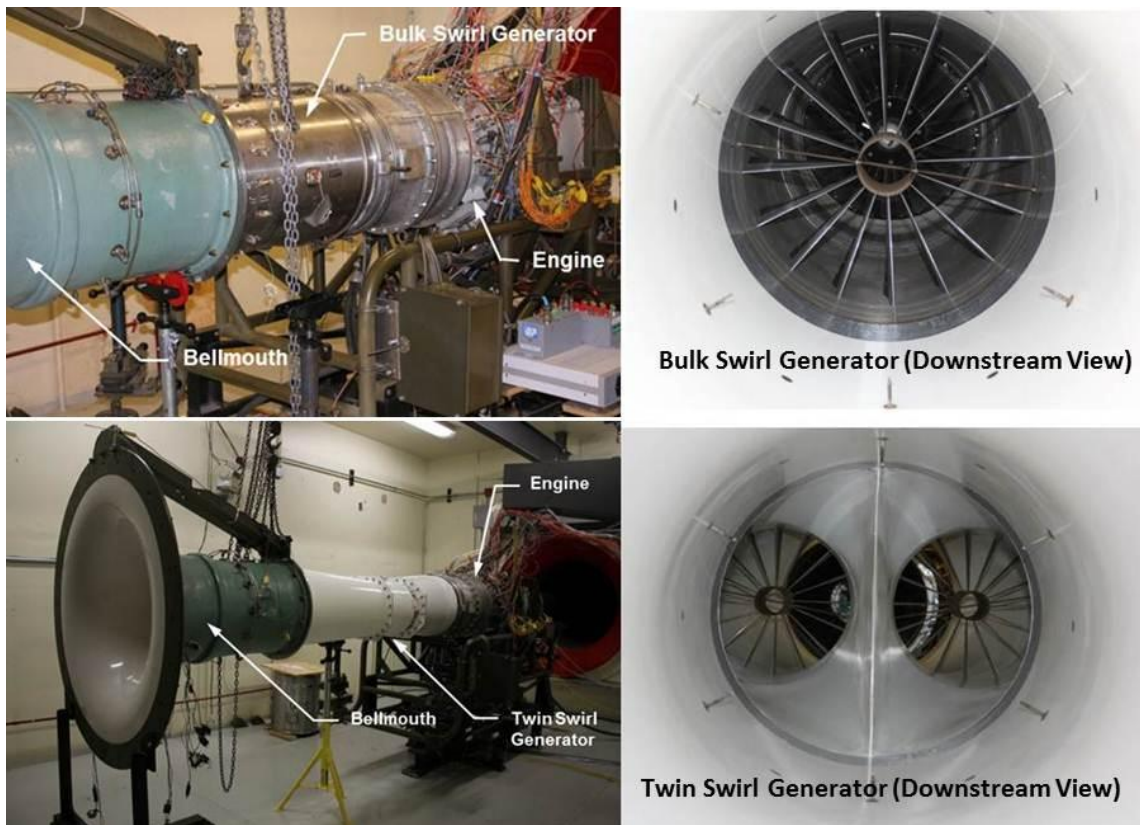


Figure 21. AEDC-Supplied Swirl Generators

4.0 APPROACH

4.1 OUTLINE OF APPROACH

The following is an outline of the approach used to meet the goals of the investigation at the heart of this report. The main bullets describe the task that had to be completed in order to meet the goals of the research. The sub-bullets describe additional tasks that had to be completed in order to fulfill the task described in the main bullet.

- Implementation of Improved Graphical User Interface
 - Re-compilation of DYNTTECC/MLC Fortran code
 - Modifications to code to allow extraction of pertinent data to this particular swirl investigation
- Comparison of Pre-Test Predictions to USAFA Test Data
 - Reduction and analysis of USAFA test data
 - Re-run of original DYNTTECC/MLC model to match test data conditions
 - Analysis of error between test data and pre-test predictions
- Clean Inlet Model Calibration
 - Development of technique to align clean inlet model predictions with USAFA test data
 - Generation of total fan pressure ratio multiplier map
 - Code modification to apply multiplier map to any inlet swirl case
- Stall Criteria Investigation

- In-depth search for suitable stall determination techniques
- Analysis of various stall criteria definitions at inlet swirl conditions
- Development of alternate stall determination method and implementation into existing DYNTTECC/MLC code
- Presentation of Final Results
 - Run model with calibration and stall determination modifications in place for all tested swirl conditions
 - Plotting and analysis of final results against USAFA test data

4.2 IMPLEMENTATION OF GRAPHICAL USER INTERFACE

Since the completion of the previous investigation by Fredrick, a new and improved DYNTTECC/MLC graphical user interface (GUI) was developed. This easy to use and improved GUI brings this particular modeling and simulation product into the analysis domain for novice users. The GUI now operates using the LabView Run Time Engine, and allows for greatly improved machine efficiency and plotting capability. To allow for the integration of the updated GUI with the existing DYNTTECC/MLC Fortran code, significant work was required and countless hurdles had to be overcome. Figure 22 shows a typical view of the GUI in use.

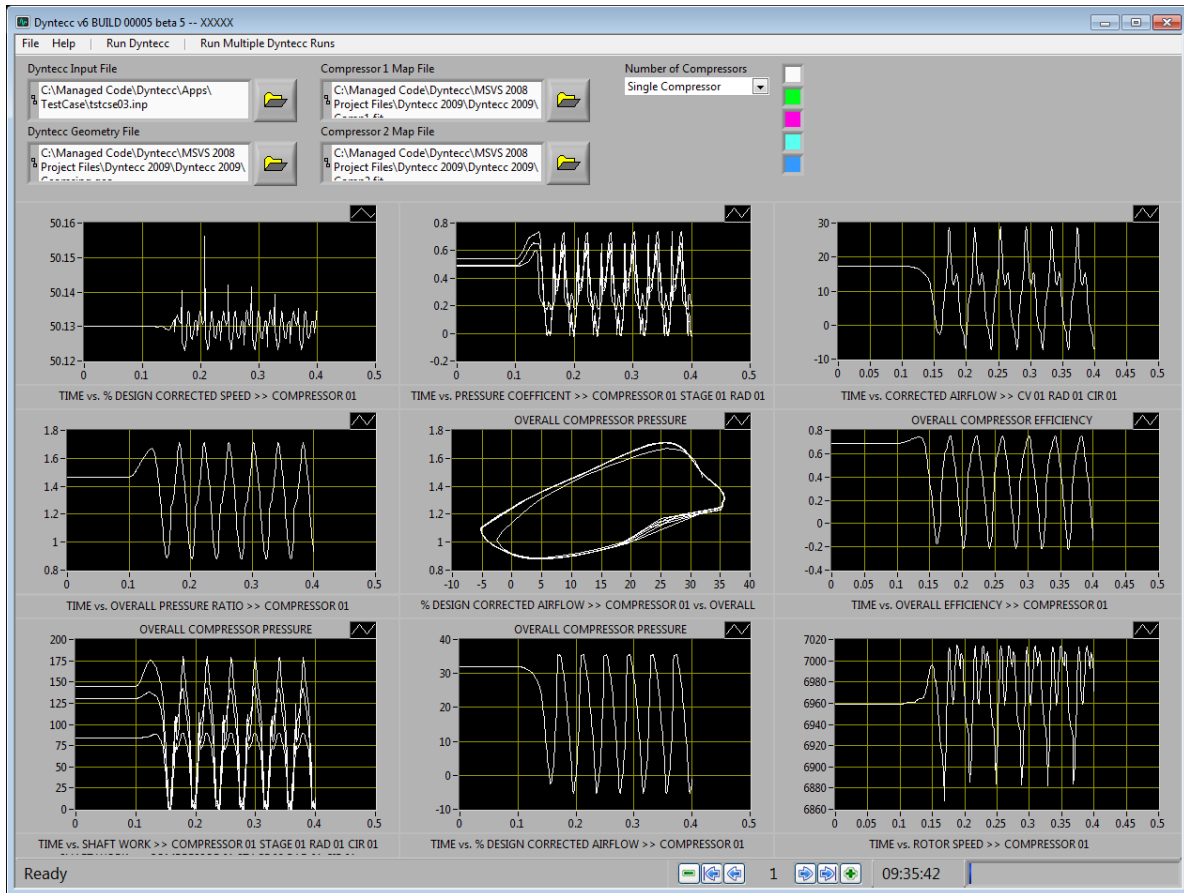


Figure 22. Updated DYNTECC/MLC GUI

4.3 USAFA TEST DATA COMPARISON

At the conclusion of the F109 inlet swirl test conducted at the United States Air Force Academy, the data were reduced for analysis purposes. The fan stall points were determined and plotted on compressor maps. It was noticed almost immediately that the actual effects of swirl on fan performance and operability did not agree with the model predictions generated by Fredrick pre-test. The reason for this was not clear at the onset of this work, so the pre-test model predictions were plotted against the reduced test data for the clean inlet

and all swirl cases available. It should be noted that the actual swirl conditions tested varied somewhat relative to the swirl angles used in the pre-test prediction. The model developed by Fredrick was re-run at the as-tested conditions for the purpose of the following plots.

The level of agreement between the pre-test predictions and the actual test data for all inlet swirl conditions can be determined from Figure 23 through Figure 28. Although the clean inlet model predicted stall line was in agreement with the test data, the overall speed line projections were not in direct agreement, as seen in Figure 23. However, for the remaining inlet swirl cases, in general, very little agreement was found between test data and model predictions. The error between model predicted stall and test data stall for swirl could be as high as 4.8% total fan pressure ratio.

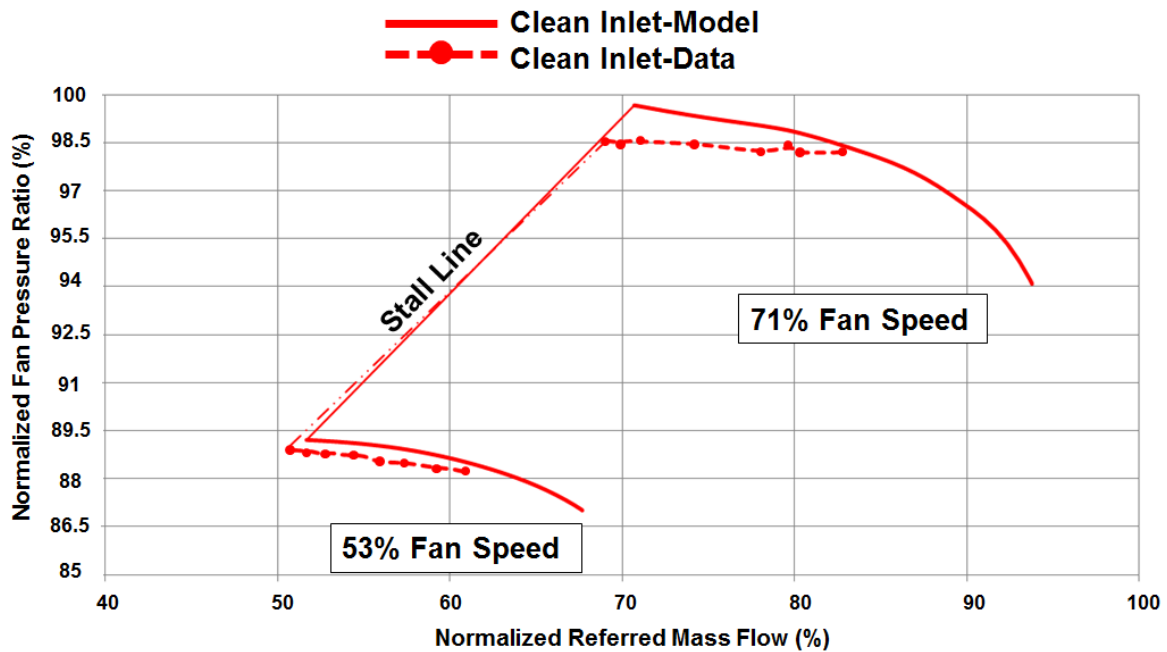


Figure 23. Normalized Clean Inlet Pre-Test Prediction

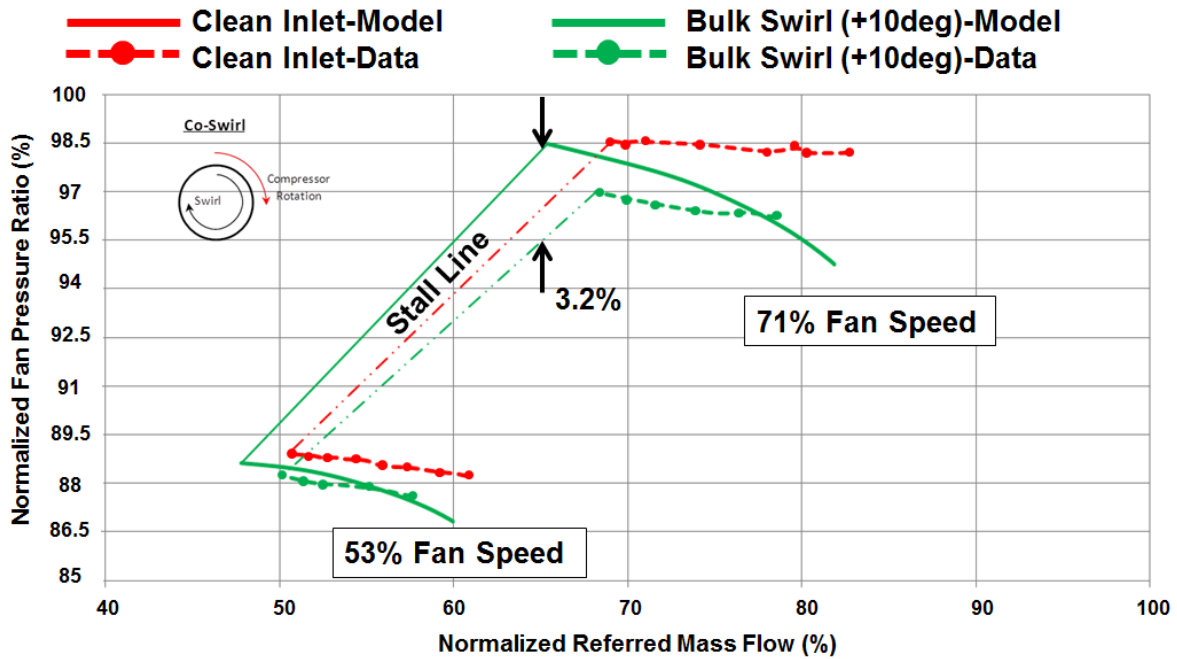


Figure 24. Normalized Bulk Swirl (+10deg) Pre-Test Prediction

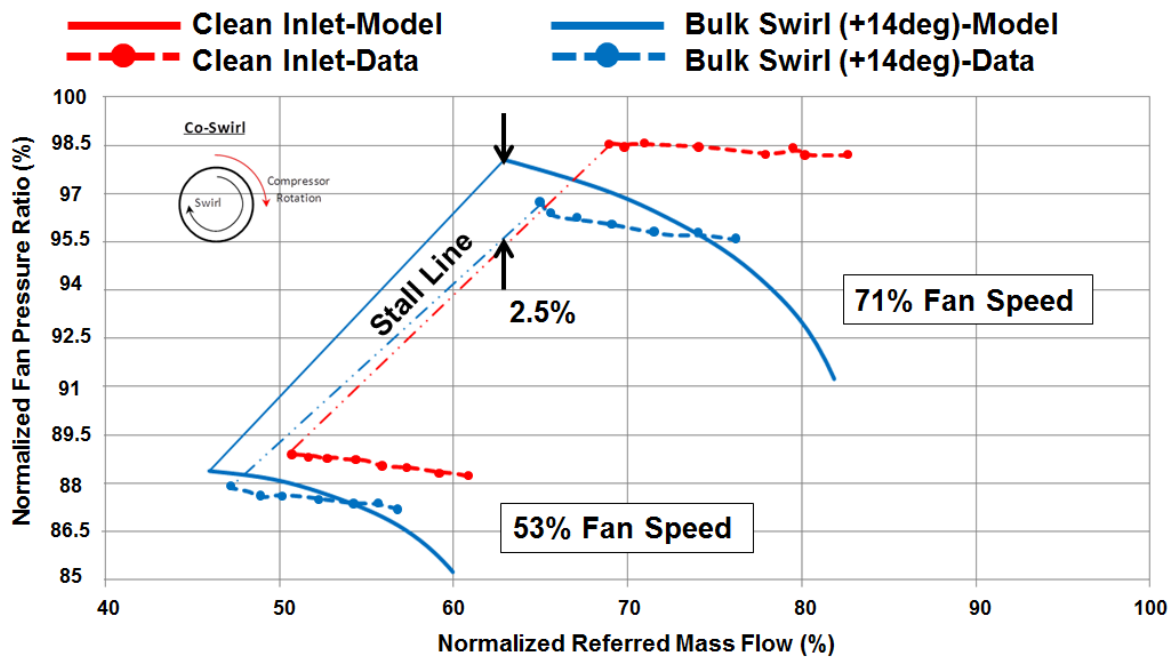


Figure 25. Normalized Bulk Swirl (+14deg) Pre-Test Prediction

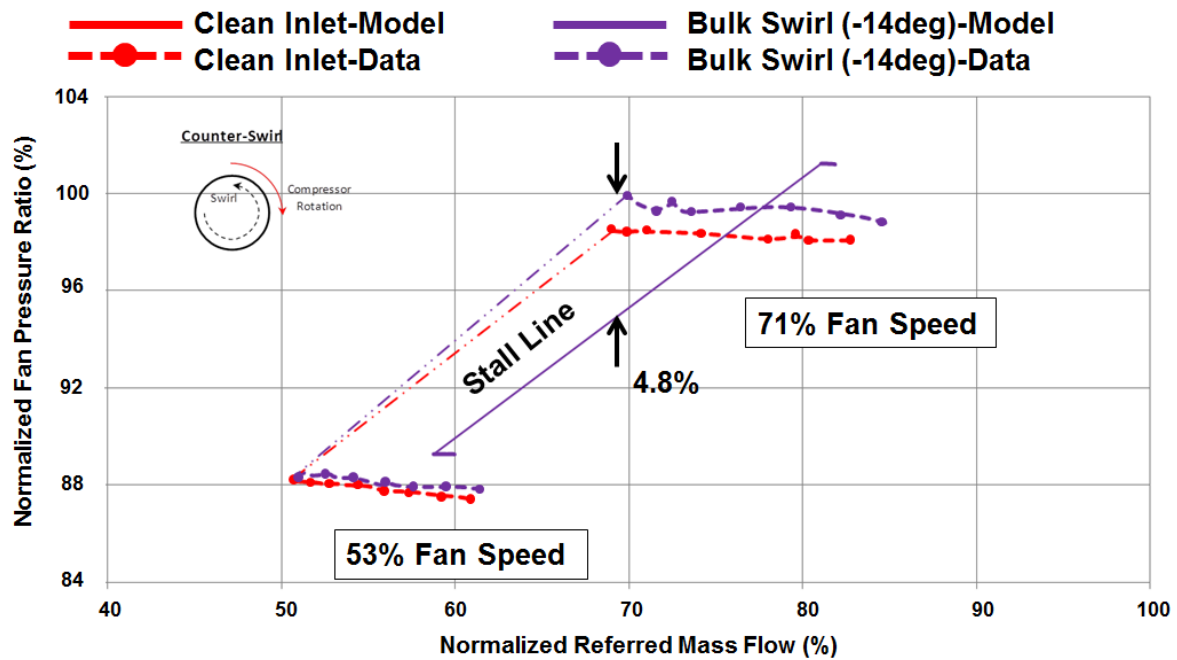


Figure 26. Normalized Bulk Swirl (-14deg) Pre-Test Prediction

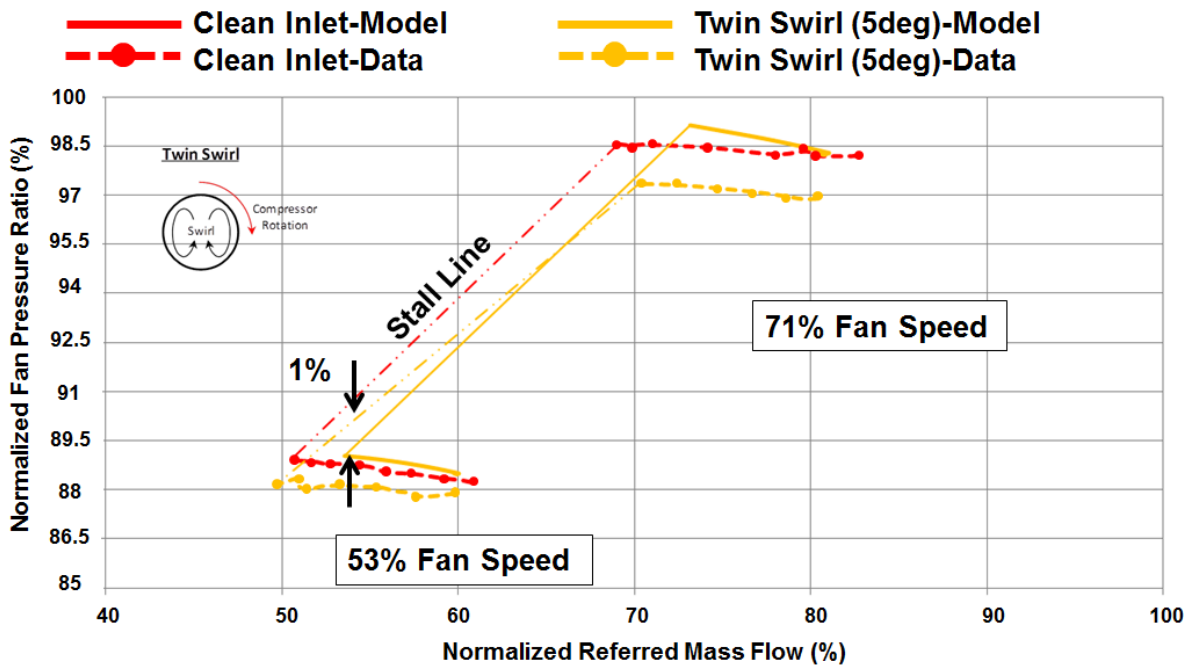


Figure 27. Normalized Twin Swirl (5deg) Pre-Test Prediction

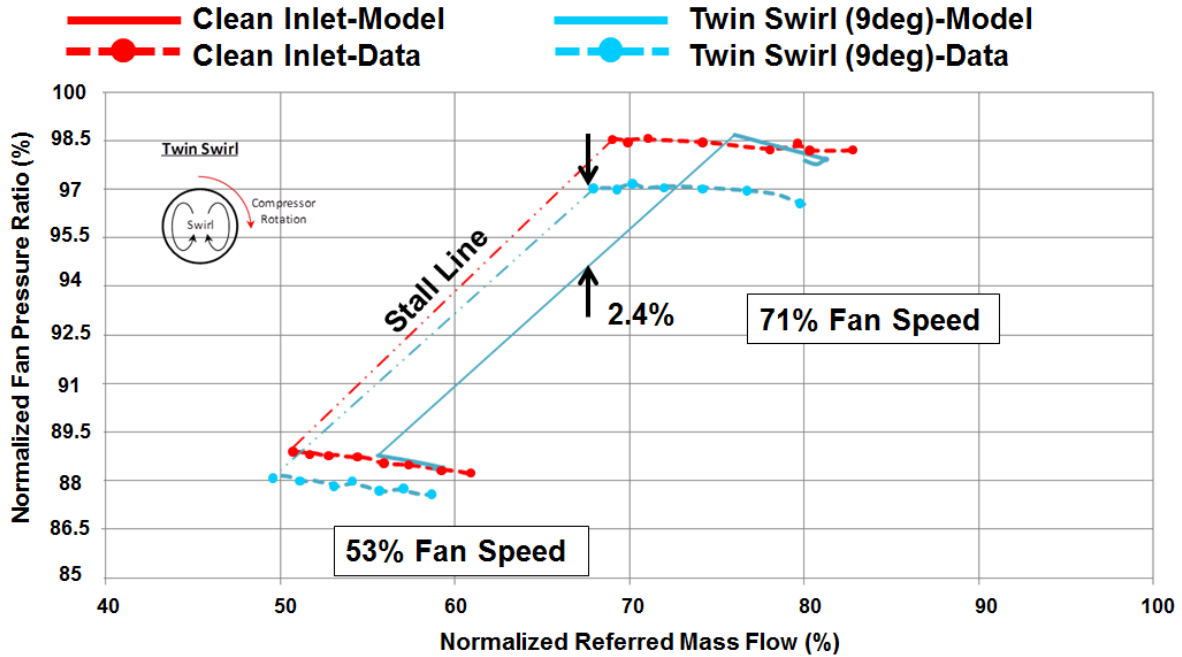


Figure 28. Normalized Twin Swirl (9deg) Pre-Test Prediction

While the reasons for model disagreement were still unknown after initial analysis, it was surmised that the loss and deviation maps generated in the previous investigation may not be entirely accurate for inlet swirl cases. These particular maps were generated using an F109 cycle code that has no provision for inlet swirl conditions. Therefore, it was deemed worthwhile to determine where the current inlet swirl model predictions fell on the maps. It was found that the majority of the swirl model runs produced inlet relative Mach number and incidence angle combinations that fell in the extrapolated regions of the maps. This phenomenon is presented in Figure 29 for the 14 degrees counter-swirl condition as an example. In the absence of cycle code data in these regions, it is possible that extrapolated loss and deviation levels are not representative of the actual system. Also, because of the meager amount of actual test data

available, these maps could not be verified. This constraint will be present throughout the remainder of this work, and will remain until a larger dataset can be obtained to produce new maps.

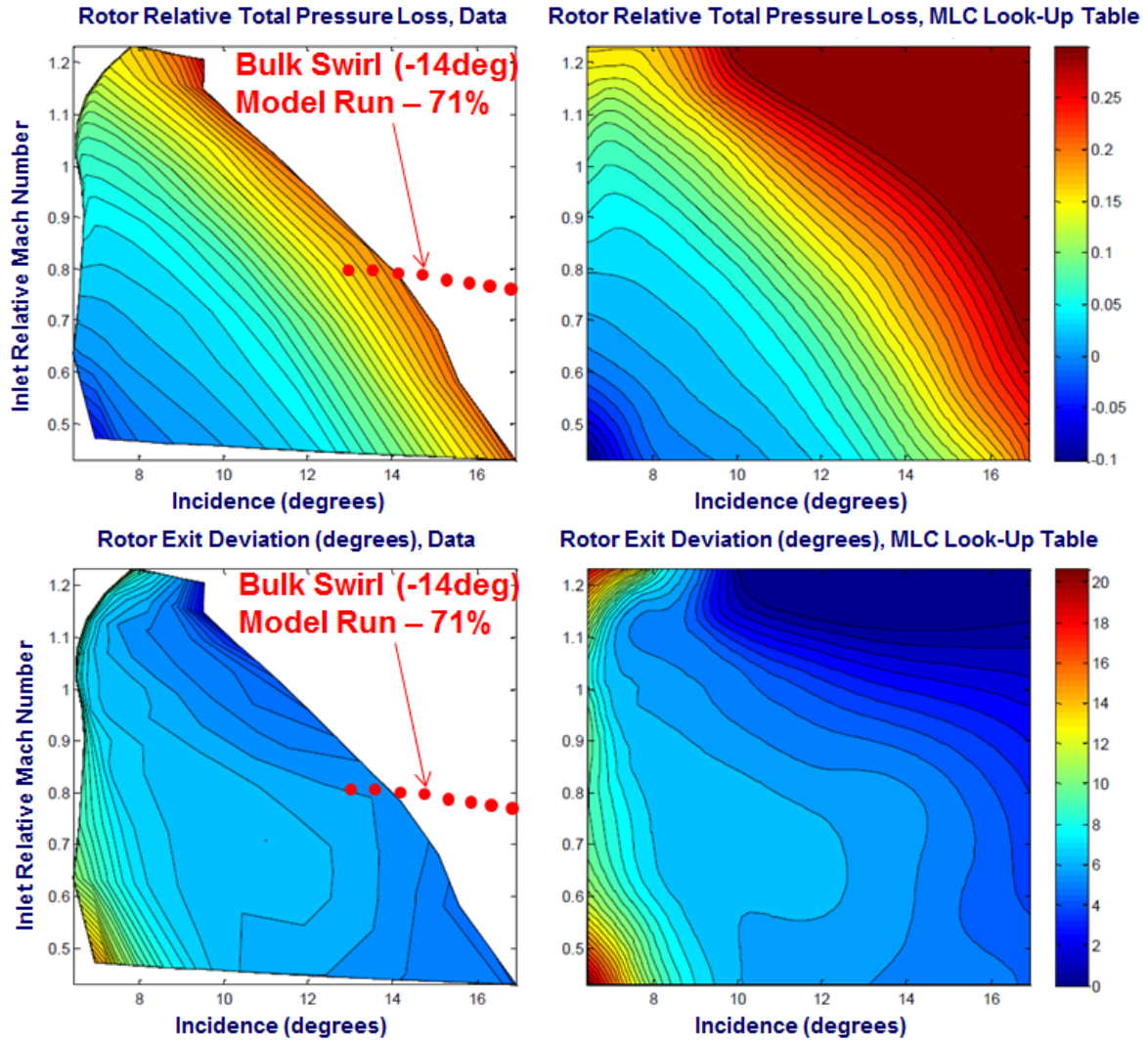


Figure 29. Rotor Loss and Deviation Effect on Pre-Test Predictions

4.4 MODEL CALIBRATION TO TEST DATA

As seen in the previous section, the initial model predictions of stall did not accurately reflect the data taken at the United States Air Force Academy. Predictions of the F109 stall line with inlet swirl were consistently in error greater than 2% total fan pressure ratio, save for the 5 degree twin swirl case, and this amount of error was deemed excessive. To help alleviate this particular issue, it was surmised that the model simply needed to be calibrated to the clean inlet data taken at USAFA. Thus, a new capability had to be added to the existing DYNTECC/MLC model to accommodate this calibration. This was accomplished using the following process. First, at a given speed and referred mass flow point, the actual fan pressure ratio was compared to the model predicted fan pressure ratio for the clean inlet at 53% and 71% fan speed. From this, a multiplier was calculated to adjust the model predicted fan pressure ratio to match the test data. A multiplier look-up table was created to cover the entire referred mass flow range under investigation, and a routine was developed to input and read this map in DYNTECC. The clean inlet multiplier was then applied to each remaining swirl case.

The results of the clean inlet baseline calibration can be seen in Figure 30. As opposed to the drastic difference in speed line level and shape evident in section 4.3, the clean inlet model predictions now fall close to the test data as would be expected. No more than a 0.3% difference in total fan pressure ratio exists between the model predictions and test data, only caused by rounding

error inherent to the creation of the multiplier look-up table. Note that no adjustment to the stall criteria determination or the loss and deviation maps was made in this calibration. The effects of the clean inlet calibration on all pertinent inlet swirl cases can be determined from Figure 31 through Figure 35. While the prediction of the stall point remained unchanged or even worsened, the proximity of the model predicted speed lines to test data improved drastically for the co-swirl cases, and improved marginally for the counter-swirl and twin swirl cases.

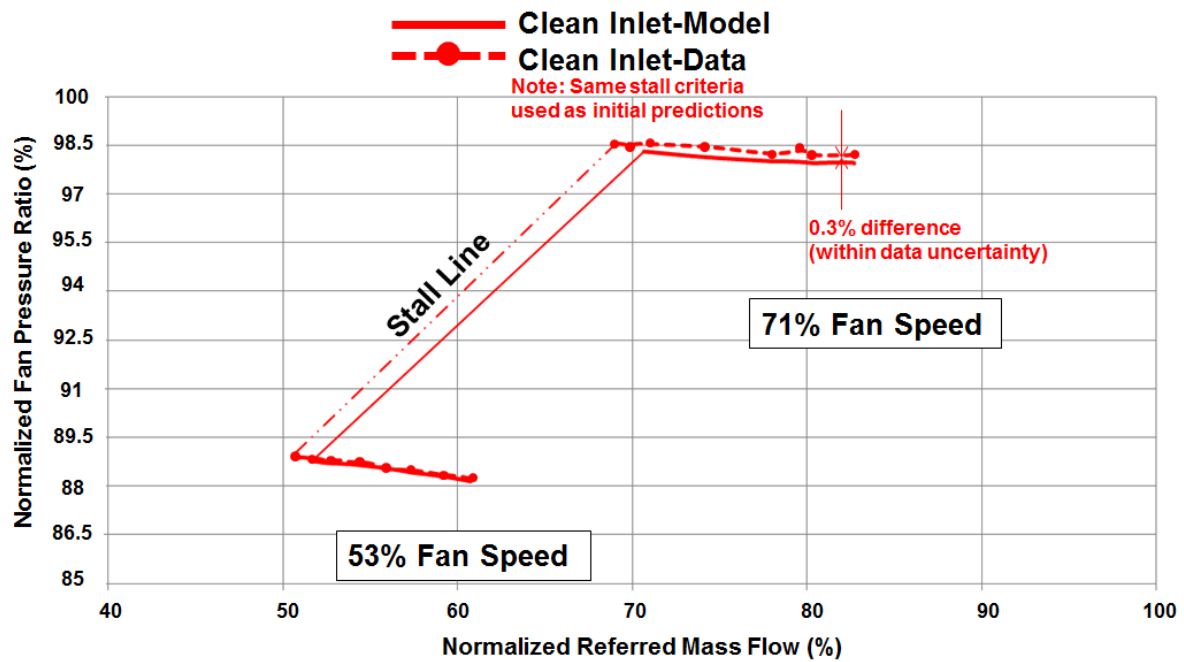


Figure 30. Normalized Clean Inlet Model Calibration

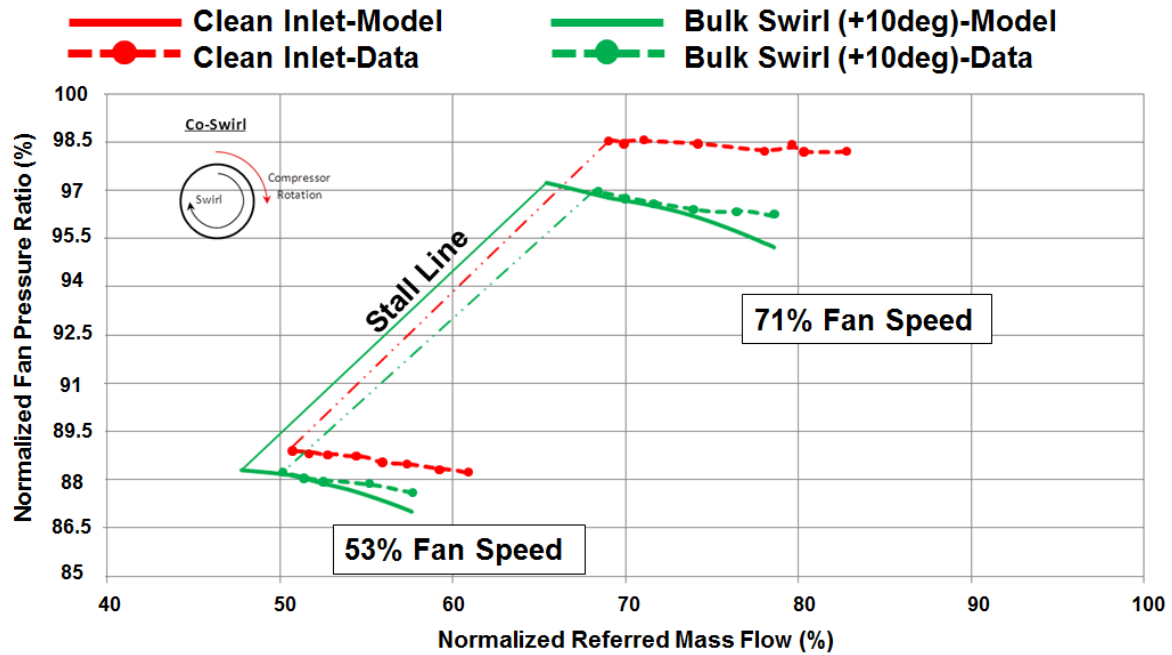


Figure 31. Normalized Bulk Swirl (+10deg) Model Calibration

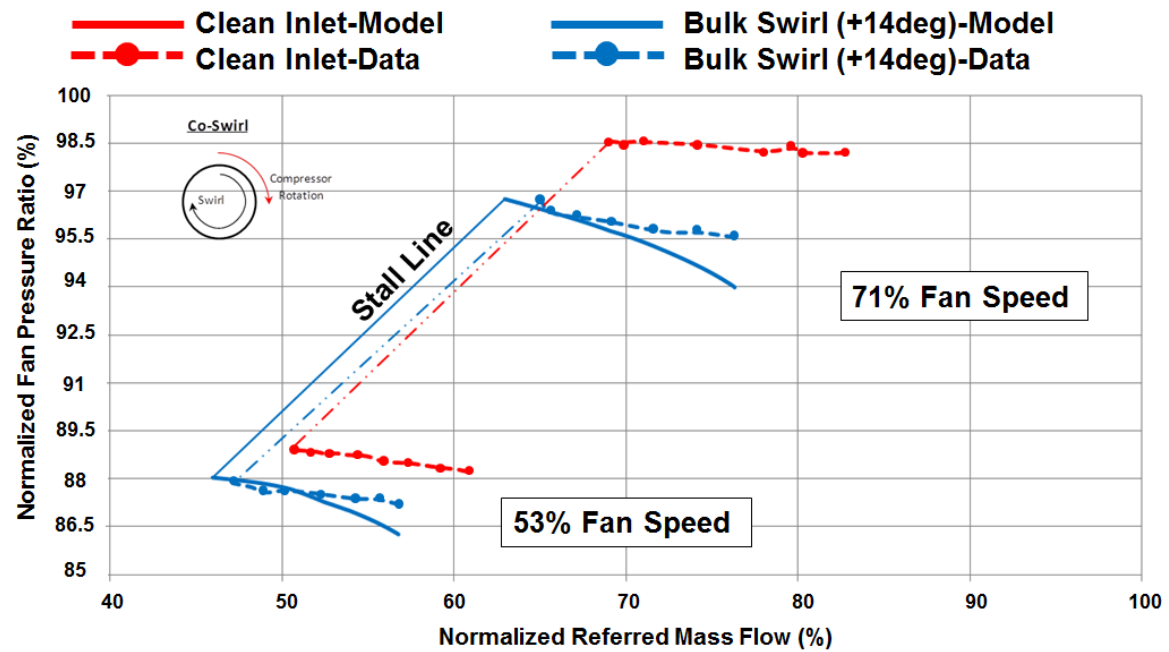


Figure 32. Normalized Bulk Swirl (+14deg) Model Calibration

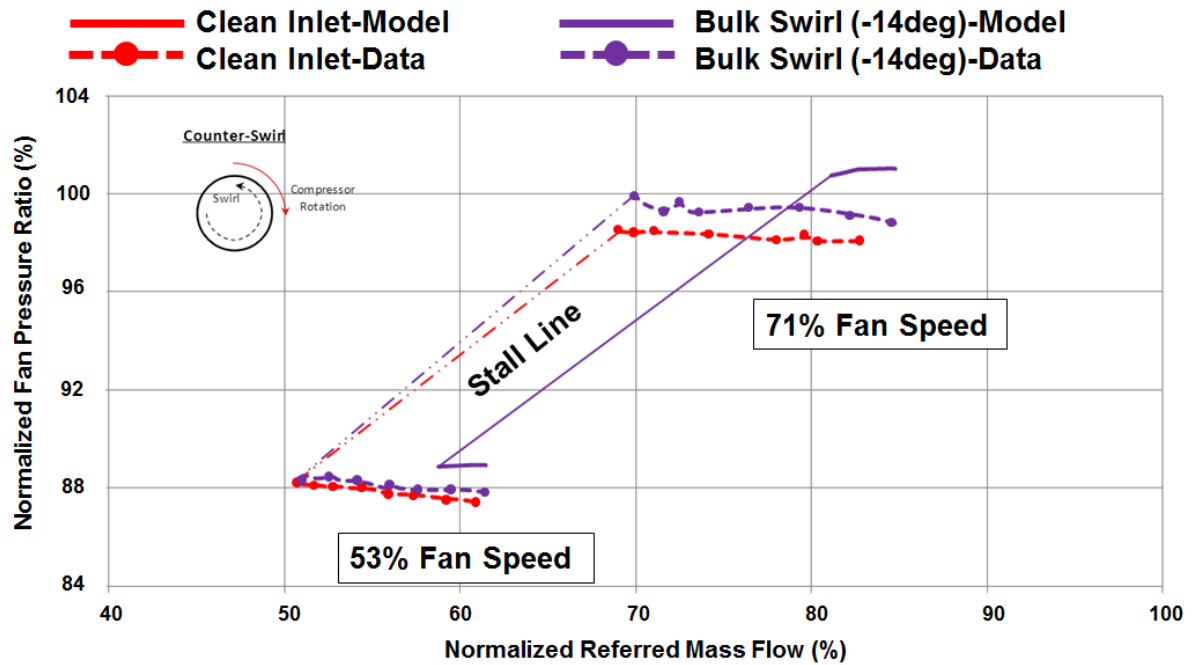


Figure 33. Normalized Bulk Swirl (-14deg) Model Calibration

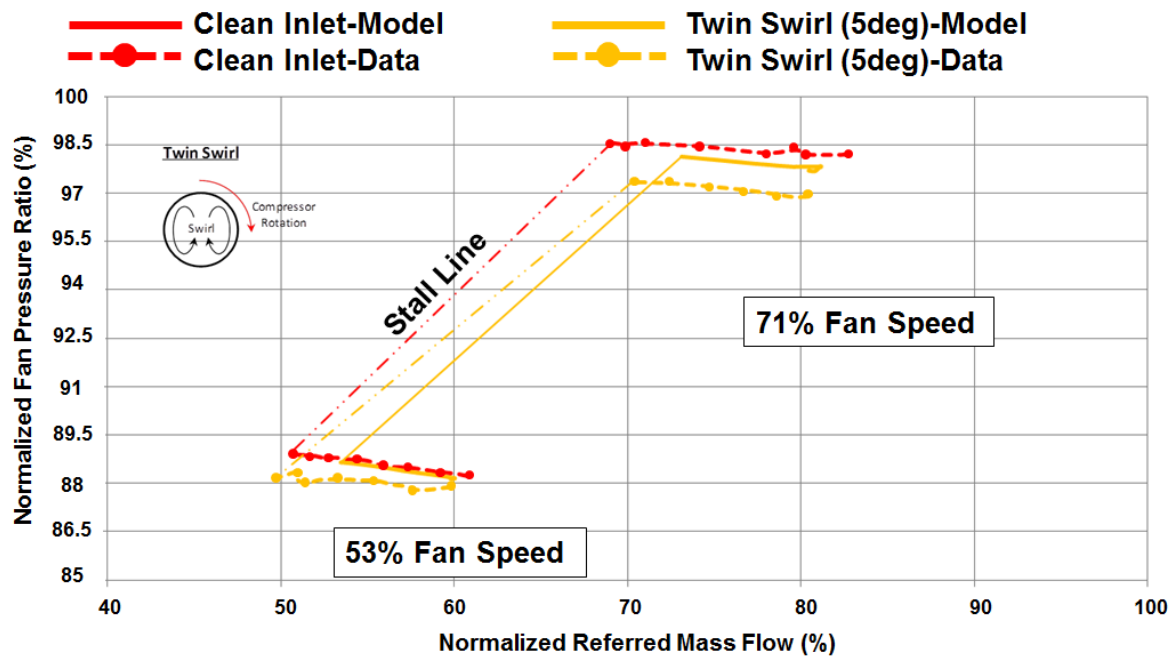


Figure 34. Normalized Twin Swirl (5deg) Model Calibration

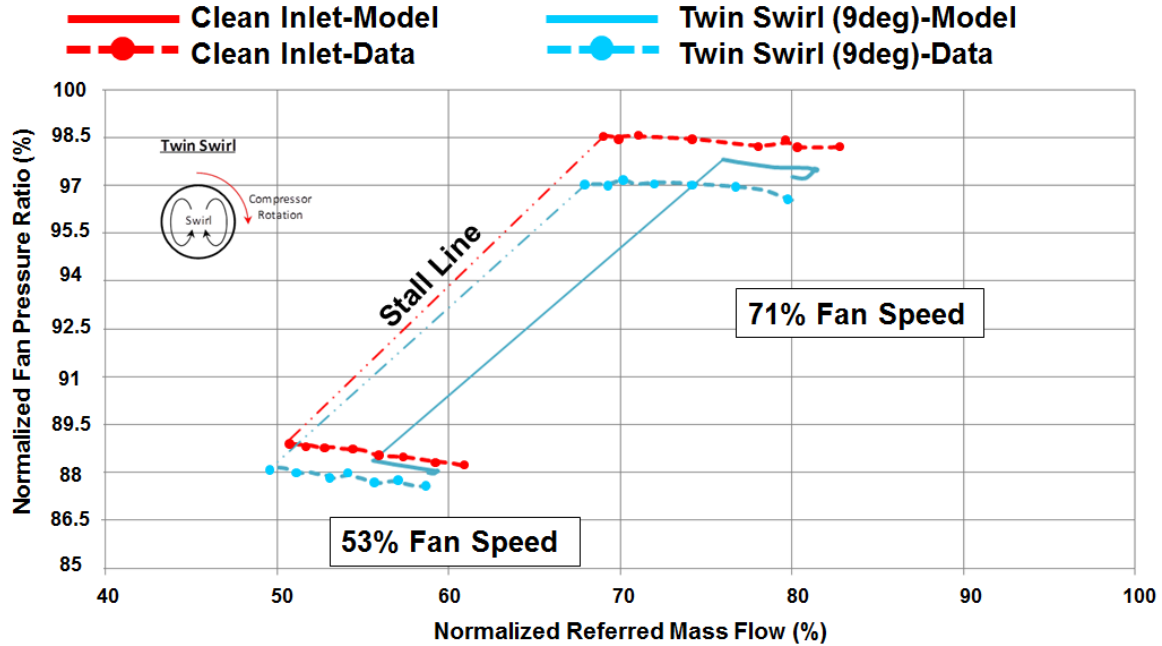


Figure 35. Normalized Twin Swirl (9deg) Model Calibration

4.5 STALL CRITERIA INVESTIGATION

After successful adjustment of the model speed line levels relative to the USAFA swirl test data by a clean inlet calibration method, it was noted that the prediction of stall was still fairly inaccurate. It was determined that it may be useful to investigate alternate model stall criteria beyond the standard diffusion factor. Several stall criteria definitions were analyzed and implemented into the code. These stall criteria definitions are explained in section 2.2. The criteria evaluated include: rotor diffusion factor, rotor diffusion factor with compressibility effect, de Haller number, static pressure rise coefficient, rotor diffusion ratio at stall condition, and rotor diffusion ratio at minimum loss condition.

The standard procedure for determining model stall with the rotor diffusion factor as outlined by Fredrick remains unchanged for the initial stall criteria

comparison. The value of each stall criteria at stall for the clean inlet case that matches test data was found. This clean inlet stall criteria value (SCV) was then used for all remaining swirl model predictions. DYNTECC will run until the calculated stall criteria value for swirl eclipses that of the clean inlet run, indicating the compression system has stalled. However, if swirl is present, that SCV at stall can vary immensely relative to the clean inlet, as seen in the model predictions given in section 4.3.

However, it was found that the alternate stall criteria provided no substantial improvement over the standard diffusion factor, which is summarized later in Figure 37. Because of this fact, a modification to the standard procedure for determining model stall was necessary. The final two stall criteria evaluated, the rotor diffusion ratio at stall condition and minimum loss condition, were nominated for further investigation. It was noticed that at clean inlet data stall, the ratio of the stalled condition diffusion ratio and the minimum loss diffusion ratio for both 71% and 53% fan speed was found to be equal. The model calculated diffusion ratio values for the clean inlet data stall for both 71% and 53% fan speed are given in Table 2.

Table 2. Alternate Diffusion Ratio Comparison

	Diffusion Ratio @ Stall: Stalled Condition (DR)	Diffusion Ratio @ Stall: Minimum Loss (DR_{op})	DR/DR_{op}
Clean Inlet (53%)	2.503	2.219	1.128
Clean Inlet (71%)	2.436	2.159	1.128

Based on this clean inlet observation, a simple multiplier of 1.128 was applied to the minimum loss diffusion ratio calculation, allowing for the model calculations of both diffusion ratio terms to be equal at clean inlet data stall. This process was then applied to the remaining inlet swirl cases. Thus, as the individual swirl cases are run in DYNTTECC, both diffusion ratio terms are calculated at each model iteration. When the ratio of the stalled condition diffusion ratio and the minimum loss diffusion ratio equals one, the compression system is considered to be stalled. A process chart describing this method can be found in Figure 36.

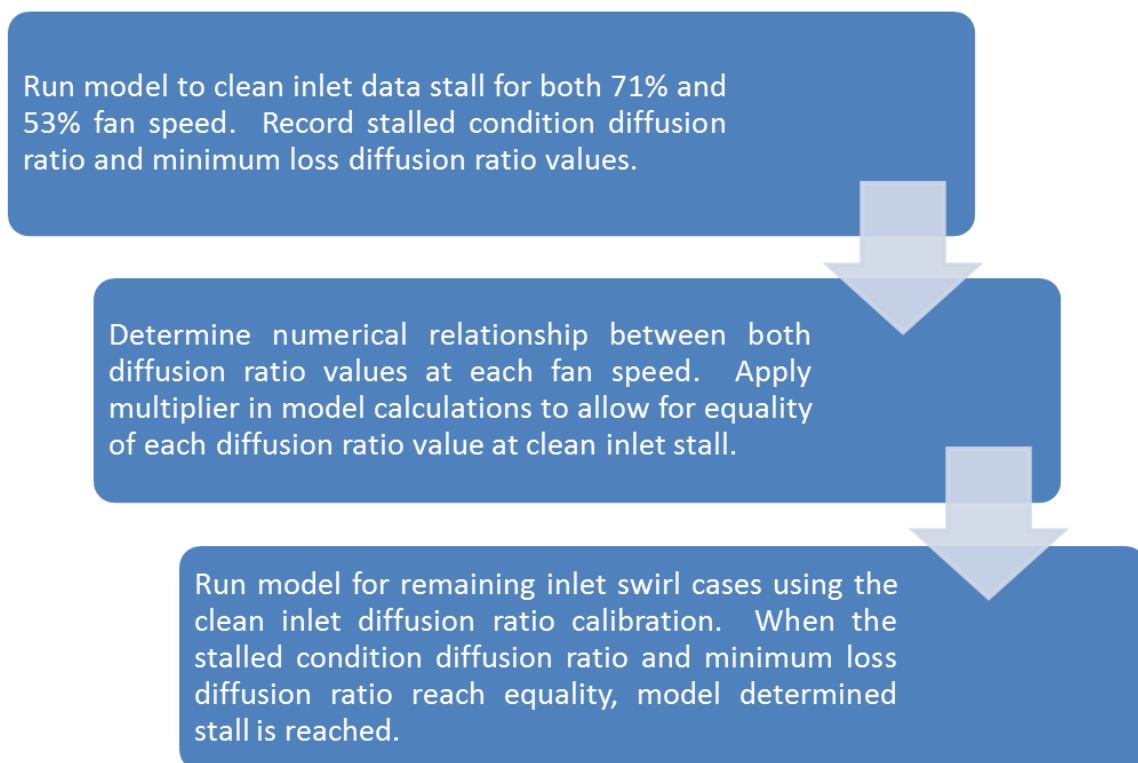


Figure 36. Alternate Diffusion Ratio Method

Based on the stall criteria investigation, the alternate diffusion ratio method was chosen as the most accurate stall criteria for inlet swirl applications. It can be theorized that this is a result of the inherent advantages of the standard rotor diffusion ratio at varying swirl angles, being the strong influence of inlet flow direction and incidence angle on stall determination that is not as evident with the standard rotor diffusion factor. As described in section 2.2.1, the standard diffusion factor (Equation 1) is calculated using inlet and exit blade velocities, while the diffusion ratio (Equation 3) is expressed in terms of inlet and outlet flow directions, as well as the change in incidence angle. In addition, the fact that stall determination is now based on the agreement of two similar yet competing rotor diffusion ratio expressions, redundancy is inherent in the determination of fan stall, thus providing a more accurate prediction than one stall criteria alone. It should be noted that this alternate diffusion ratio method is only possible because of the availability of test data and the subsequent model calibration to that test data. Since data were only obtained at two fan speed conditions, it would be of interest to gather additional data to verify that the observed diffusion ratio relationships are evident across a wider range of fan speeds.

The comparison of the alternate diffusion ratio method versus the various other stall criteria is depicted in the following plot where an evaluation of all six stall criteria definitions at 71% fan speed for both co- and counter-swirl, as well as the alternate diffusion ratio method is presented in Figure 37. The stall criteria value at clean inlet stall was found for each stall criteria definition. This stall criteria value was then used for the +14 degrees and -14 degrees swirl cases.

The stall point for each was then plotted according to the plot legend. It is evident that the alternate rotor diffusion ratio method provided substantial improvements over the competing methods in terms of proximity to the USAFA swirl test data stall lines, falling within 0.8% fan pressure ratio at a given referred mass flow for both swirl cases.

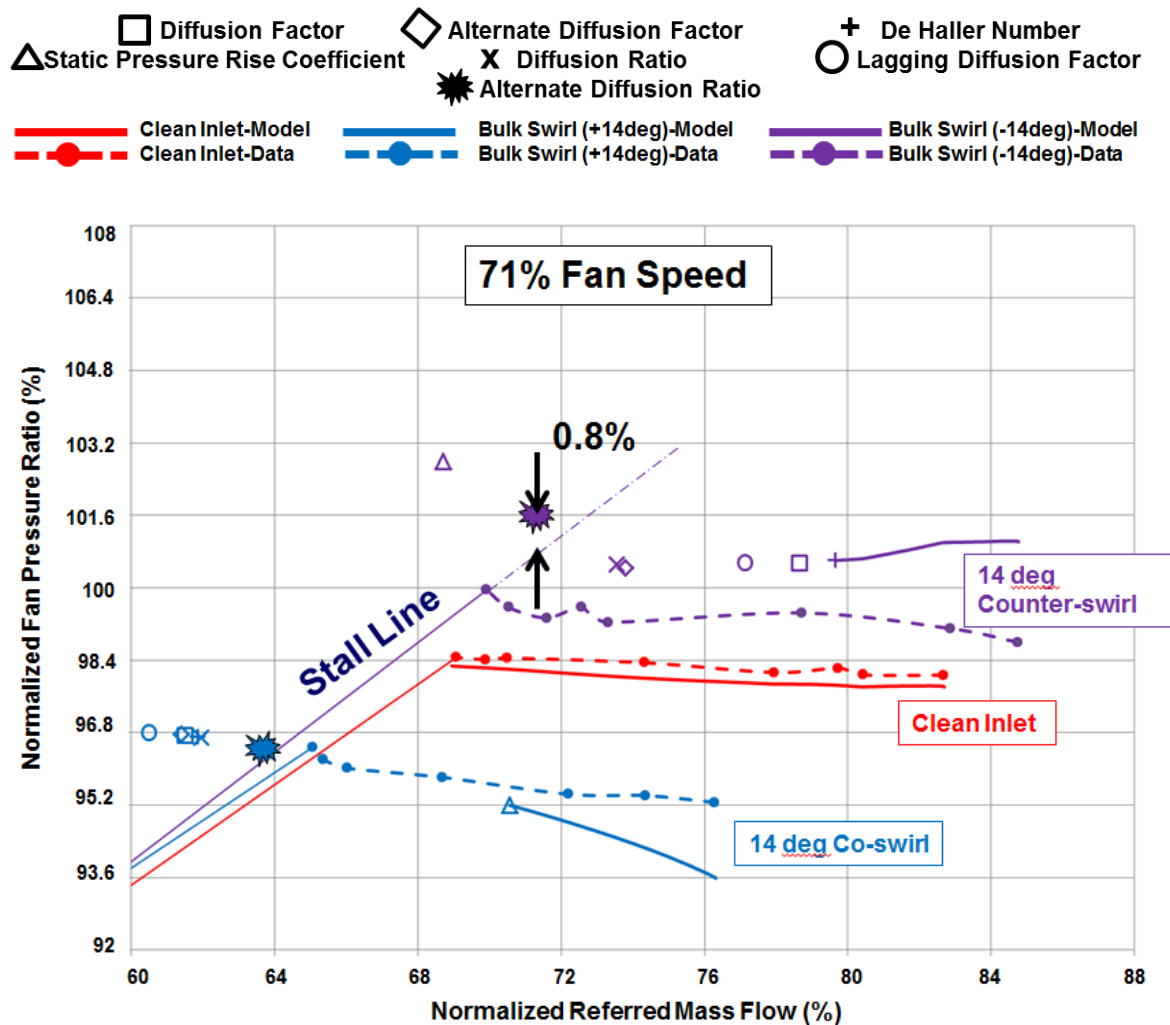


Figure 37. Stall Criteria Comparison, Normalized

Figure 38 also presents the clear superiority of the alternate rotor diffusion ratio method versus the competing stall criteria. In this plot, each swirl case was run to the data stall for all stall determination methods (excluding the lagging diffusion factor), and the stall criteria value was noted. This plot depicts the deviation of each swirl case stall criteria value from the clean inlet data stall criteria value. It is evident that the alternate rotor diffusion ratio method deviated the least from the clean inlet across all inlet swirl cases. No inlet swirl case stall criteria value using the alternate rotor diffusion ratio method eclipsed a deviation above 5%, while the competing swirl criteria all exhibited deviations greater than 10%. This shows that if the stall criteria value that correlates to the clean inlet stall value is used across all inlet swirl cases, the alternate diffusion ratio method would provide the least amount of error when predicting inlet swirl stall points.

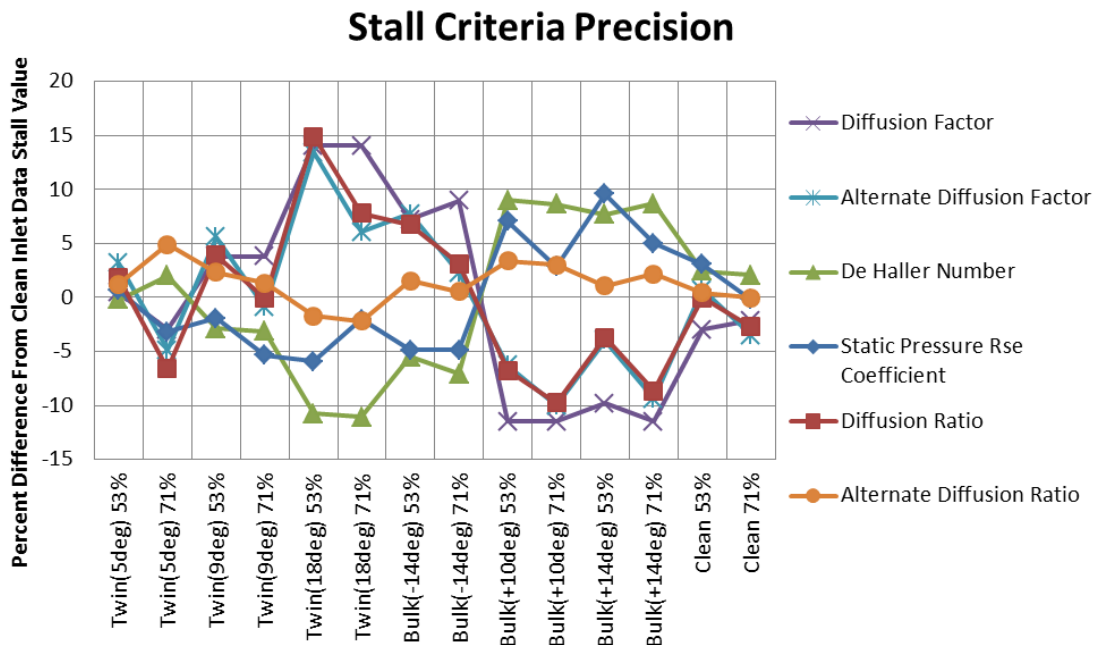


Figure 38. Stall Criteria Precision

5.0 RESULTS

After the completion of the aforementioned model calibration and stall criteria investigation, the final model predictions were generated and compared to the USAFA test data. Three types of bulk swirl were modeled to align with available test data: +10 degrees (co-swirl), +14 degrees (co-swirl), and -14 degrees (counter-swirl). In addition, two types of twin swirl were modeled to align with available test data: 5 degrees and 9 degrees. The as-tested swirl angle was input to DYNTECC, and the alternate diffusion ratio method was used as the deciding stall criteria (Section 4.5). The model predictions are plotted against the USAFA inlet swirl test data for comparison and analysis at the two speeds where data were taken: 53% and 71% fan speed. The clean inlet test data is also present on each plot to provide a stable frame of reference for the effects of inlet swirl.

Figure 39 depicts the clean inlet test data compared to the final clean inlet model prediction. Because the model was calibrated to the clean inlet data, significant agreement between model and data exists. The speed line levels are within 0.3% fan pressure ratio at a referred mass flow as a result of the model calibration described in section 4.4. Also, since the alternate diffusion ratio method was calibrated to the clean inlet as described in section 4.5, the model predicted stall fan pressure ratio for each fan speed is analogous to test data stall.

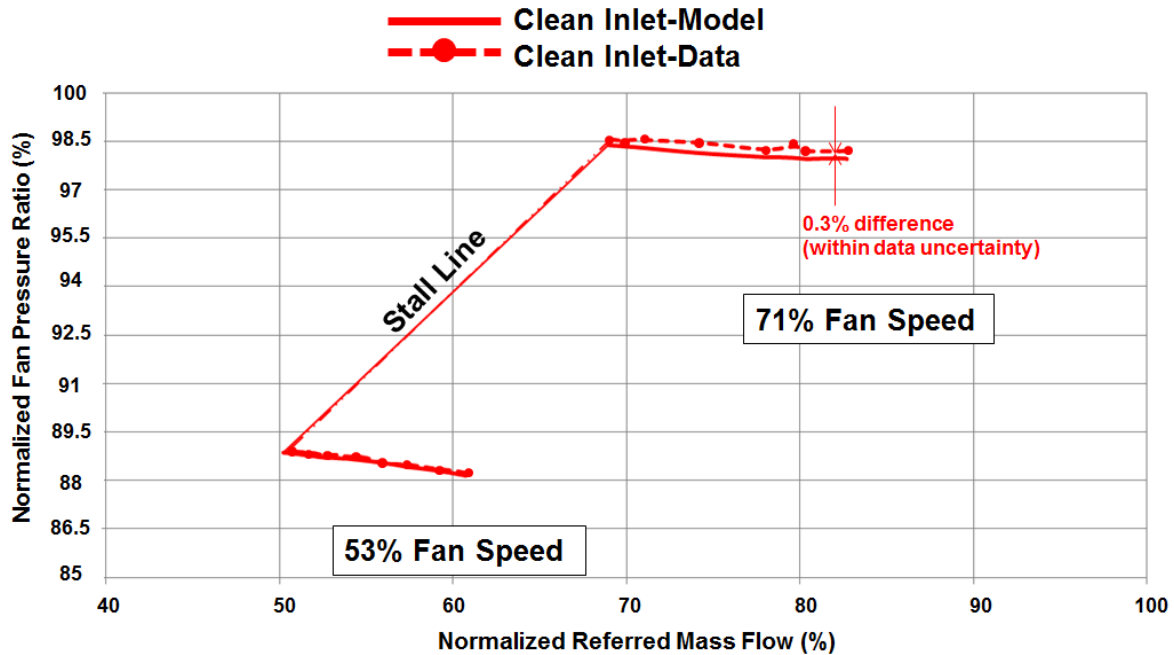


Figure 39. Normalized Clean Inlet Final Prediction

5.1 BULK SWIRL

Figure 40 depicts the $+10^\circ$ bulk swirl test data compared to the $+10^\circ$ bulk swirl model prediction. As seen in section 4.4, the clean inlet model calibration significantly improved the speed line alignment at the co-swirl cases, especially near stall. Using the alternate diffusion ratio method as calibrated to the clean inlet, the model predicted stall fan pressure ratio was within 1.6% of the test data at a given referred mass flow and referred fan speed, which represents a clear improvement over the original model prediction that exhibited an error of 3.2%.

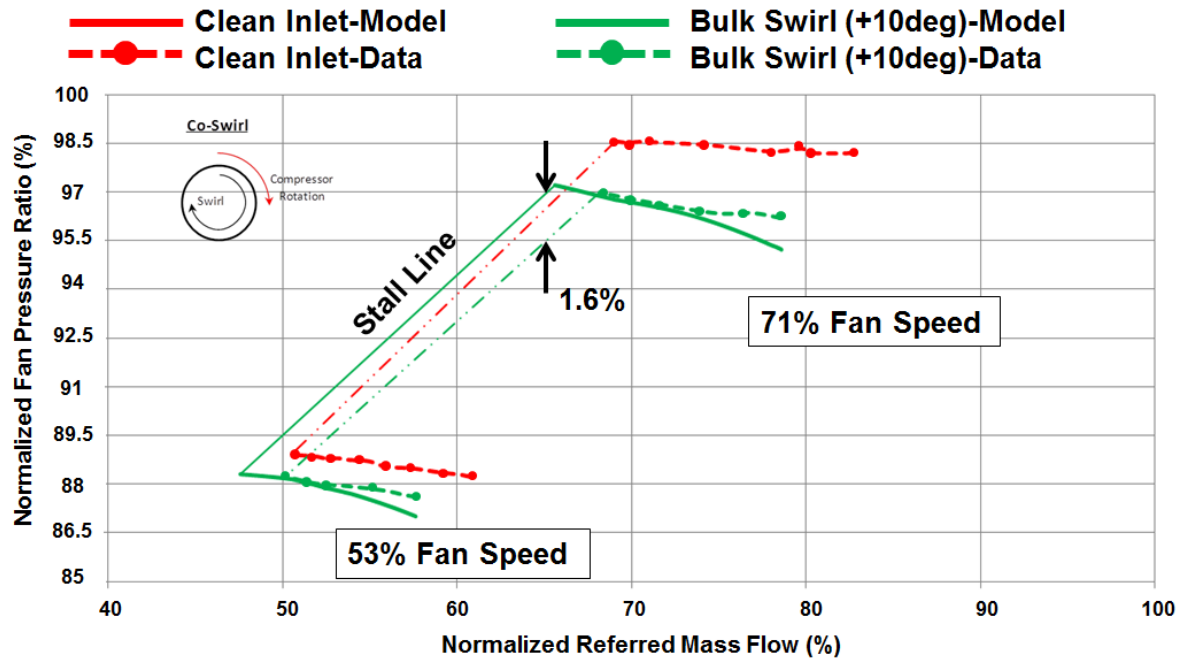


Figure 40. Normalized Bulk Swirl (+10deg) Final Prediction

Figure 41 depicts the $+14^\circ$ bulk swirl test data compared to the $+14^\circ$ bulk swirl model prediction. Using the alternate diffusion ratio method as calibrated to the clean inlet, the model predicted stall fan pressure ratio was within 0.5% of the test data at a given referred mass flow and referred fan speed, which represents a marked improvement over the original model prediction that exhibited an error of 2.5%.

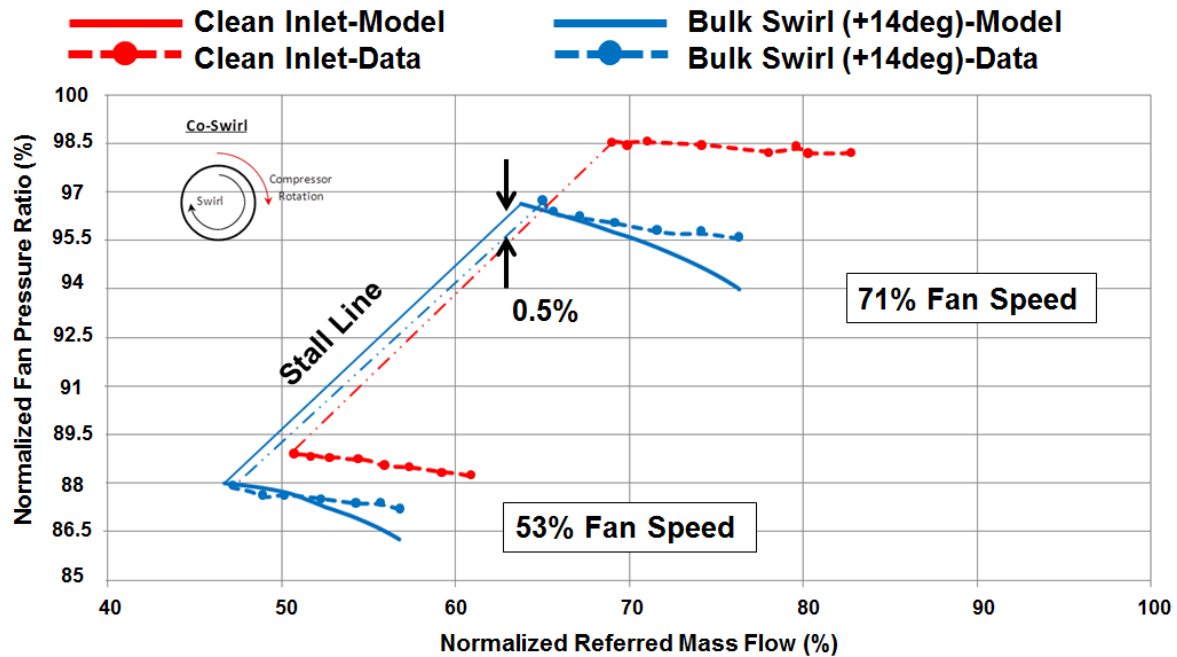


Figure 41. Normalized Bulk Swirl (+14deg) Final Prediction

Figure 42 depicts the -14° bulk swirl test data compared to the -14° bulk swirl model prediction. As mentioned previously, the clean inlet model calibration significantly improved the speed line alignment at the co-swirl cases near stall. However, even though the counter-swirl case showed improved agreement compared to the original model predictions, the counter-swirl case did not respond as well to the clean inlet calibration as the co-swirl cases because of the extreme speed line misalignment of the initial predictions. Using the alternate diffusion ratio method as calibrated to the clean inlet, the model predicted stall fan pressure ratio was within 0.8% of the test data at a given referred mass flow and referred fan speed, which represents a substantial improvement over the original model prediction that exhibited an error of 4.8%.

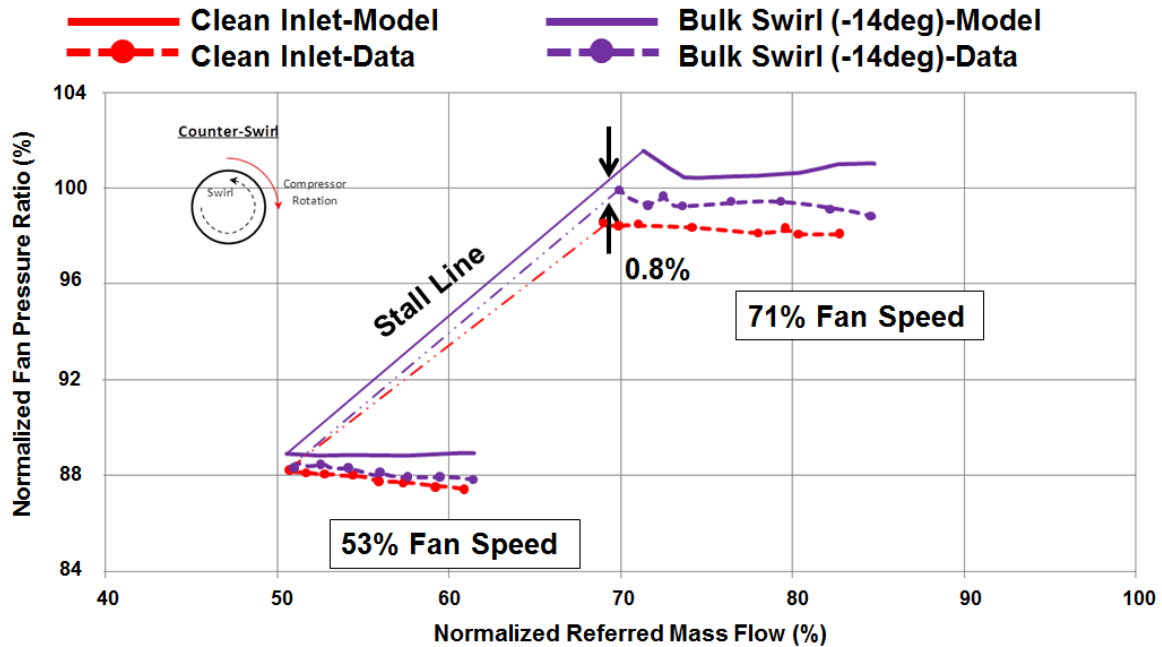


Figure 42. Normalized Bulk Swirl (-14deg) Final Prediction

5.2 PAIRED SWIRL

Figure 43 depicts the 5° twin swirl test data compared to the 5° twin swirl model prediction. As mentioned previously, the clean inlet model calibration significantly improved the speed line alignment at the co-swirl cases near stall. However, even though the twin swirl case showed improved agreement compared to the original model predictions, the twin swirl case did not respond as well to the clean inlet calibration as the co-swirl cases because of the extreme speed line misalignment of the initial predictions. Using the alternate diffusion ratio method as calibrated to the clean inlet, the model predicted stall fan pressure ratio was within 1.9% of the test data at a given referred mass flow and referred fan speed. Although this error is within the 2% threshold referenced

earlier in this report, it represents a definitive step back from the original model prediction that exhibited a maximum error of 1%. It would be of interest to take additional data at this inlet swirl case to verify the initial data is in fact accurate, particularly at the 71% fan speed condition.

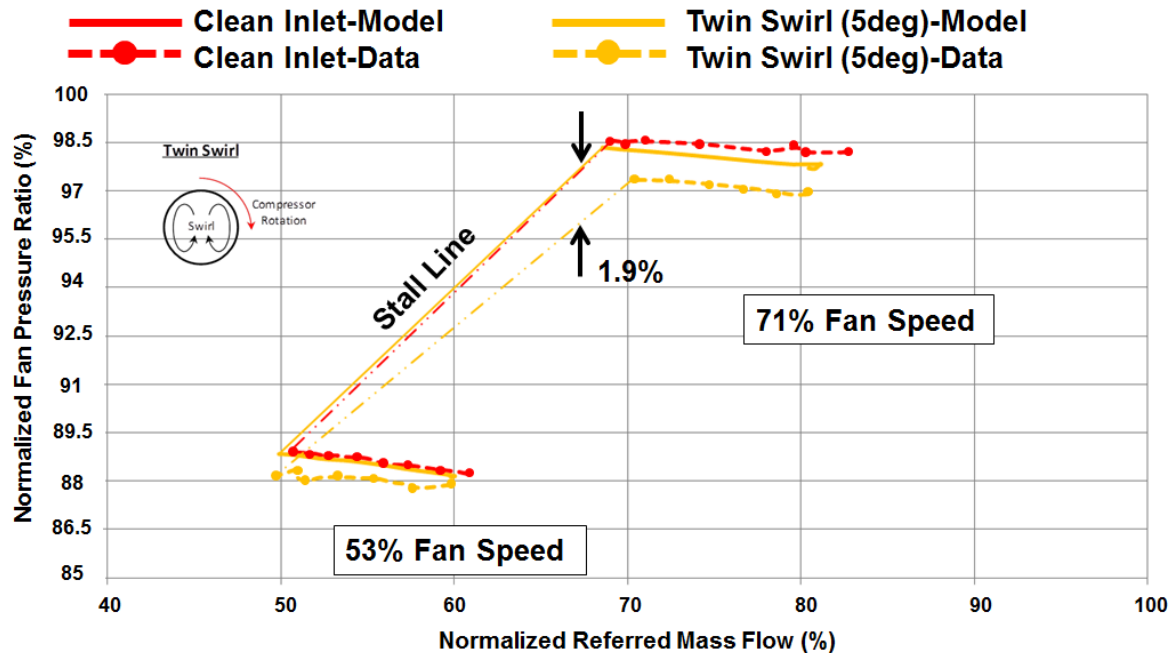


Figure 43. Normalized Twin Swirl (5deg) Final Prediction

Figure 44 depicts the 9° twin swirl test data compared to the 9° twin swirl model prediction. Using the alternate diffusion ratio method as calibrated to the clean inlet, the model predicted stall fan pressure ratio was within 0.6% of the test data at a given referred mass flow and referred fan speed, which represents a definitive improvement over the original model prediction that exhibited an error of 2.4%.

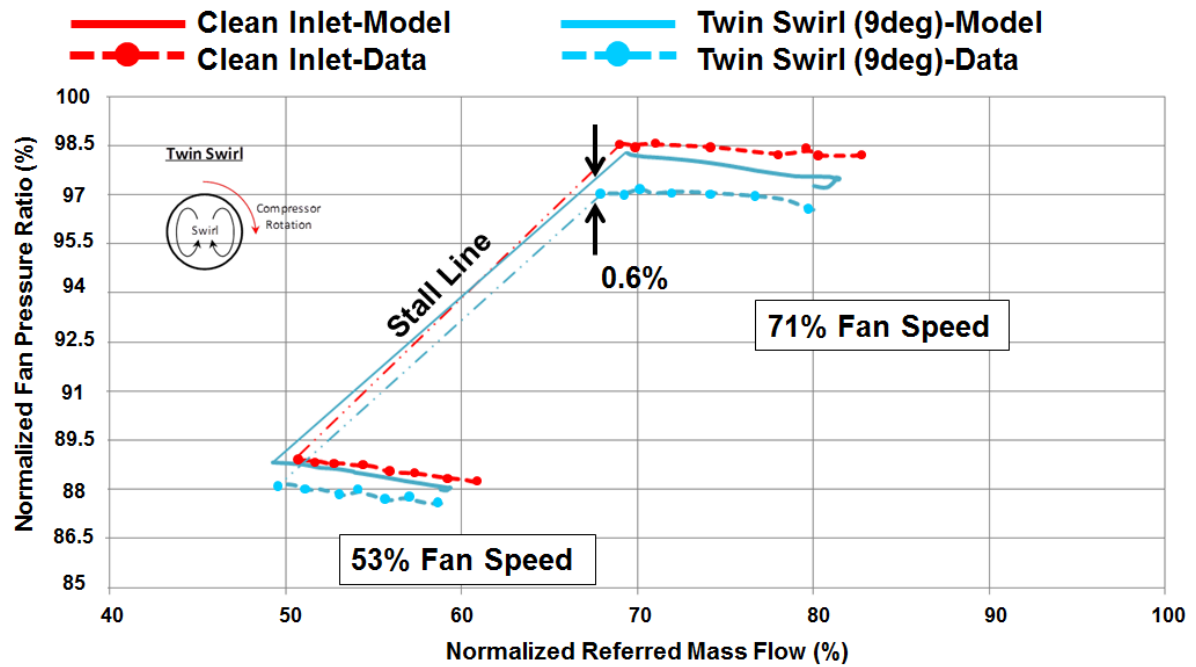


Figure 44. Normalized Twin Swirl (9deg) Final Prediction

6.0 CONCLUSIONS AND RECOMMENDATIONS

The work contained in this thesis has provided a substantial improvement to the development of the one-dimensional parallel compressor model used for the prediction of inlet swirl effects on fans and compressors. Building upon previous work completed at AEDC, the modified DYNTECC/MLC model was validated against test data gathered at the United States Air Force Academy. To correct model inaccuracies relative to the USAFA test data, the model reported herein was calibrated to the clean inlet data and an alternative stall determination method was proposed. The alternate diffusion ratio method, along with the clean inlet calibration, provided a marked improvement in the accuracy of the model in matching available swirl test data. The prediction of the fan stall pressure ratio for all inlet swirl conditions tested is within 2% of the ground test stall point at the same referred fan speed and referred mass flow.

However, the model is not perfect, and improvements can still be made to increase the predictive capabilities of the model. Although the alternate diffusion ratio stall criteria greatly improved the accuracy of the stall prediction, there does not seem to be a one size fits all approach for both bulk and paired swirl patterns. Future refinements can be made in several areas to possibly improve the accuracy of the model. One such technique could be to employ Computational Fluid Dynamics (CFD) to verify model boundary conditions specified at the exit of the fan. CFD can also be used to refine the loss and deviation look-up maps that are internal to the model, as opposed to the current maps that were generated by

the one-dimensional mean line code. It may also be worthwhile to investigate the integration of a version of the Streamline Curvature Code [10] in place of mean line code to supply the pressure ratio and temperature ratio inputs to DYNTECC. Finally, it is important that additional F109 engine testing with inlet swirl is completed to ensure that current data used in this report is repeatable, as well as fill out the map with additional speed lines.

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