Performance Correction Models for Advanced Turbofan Engines

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Advanced turbofan engine airflow and fan operating lines are controlled in order to optimize performance while maintaining adequate stability margin. Consequently, controls are configured to vary scheduled parameter values throughout the flight envelope. It is the objective of this paper to investigate the effects that control-related changes have on the utility of several possible performance correction models. Performance correction models are used to infer performance at conditions other than those tested to determine specification compliance and for standardization of flight test data. Models now used in industry plus ones developed by the authors are examined systematically for sensitivity to errors associated with changes in control-scheduled, mode, trim level, and engine quality.

Nomenclature

T = total temperature at engine inlet
P = total pressure at engine inlet
ΔT_{STD} = temperature at condition of interest minus standard day temperature
KT = temperature correction derived form log series expansion
x = an environmental condition other than standard day at which performance is measured
S = standard condition

Introduction

TRADITIONALLY, dimensional analysis has provided the basis for inferring generalized turbine engine performance characteristics from a relatively small set of test data. Dimensional analysis, alone, is sufficient as long as engines are relatively simple in geometry or control. Recently developed turbofan engines have incorporated as much as three types of variable geometry (fan inlet guide vanes, compressor variable stators, and exhaust nozzles) in an attempt to optimize performance while maintaining adequate stability margin. Furthermore, engine controls have become more sophisticated and/or more complex to take advantage of the variability in turbomachinery operation afforded by the variable geometry.

The purpose of this paper is to examine two turbofan engines (one designed for an advanced bomber and the other for an advanced fighter) which employ different approaches toward optimizing performance and stability to illustrate how performance correction methodology must be developed carefully so that accurate inferences may be drawn concerning performance at other than test conditions. It will be shown how thermodynamic cycle and control methodology affect the determination of the most accurate performance methodology.

The necessity of correcting data revolves around two areas: correction for specification compliance and correction to standardize data. Specification compliance testing occurs under near sea-level static conditions in factory test cells where atmospheric conditions are nonstandard, in altitude test facilities where the desired simulated flight conditions cannot be established perfectly, and in flight tests where test conditions must be corrected to standard or tropical day conditions. Standardization also involves the depiction of aircraft performance data in the Pilots Handbook.

Both of the engines examined in this paper are liminted to a maximum value of turbine inlet-temperature. Prior to reaching these limiting values of turbine inlet temperature, the engines are governed to a scheduled value of one or both rotor speeds. The engines' thrust characteristics as a function of engine inlet temperature vary significantly between the two control modes of rotor speed or turbine inlet temperature. Generally, the control schedules for rotor speed control are so constructed as to maintain essentially constant thrust. However, when on turbine inlet temperature control, thrust level is strongly dependent on engine inlet temperature. This behavior is illustrated in Fig. 1.

It is apparent that the control mode effects both the slope and, therefore, the path to be taken when correcting data from a nonstandard to standard day test condition. The break point between rotor and temperature limit control modes (commonly called the theta-break) is basically a function of engine inlet temperature. Obviously, engine quality will cause the theta-break to shift for a given engine about a mean theta-break line described by an average engine. Also, a theta-break will shift with altitude and Mach number as a function of hot, cold, or standard atmosphere. This is shown schematically in Fig. 2.

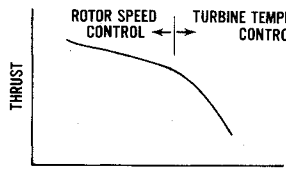

Fig. 1 Illustration of change in control mode due to engine inlet temperature change.

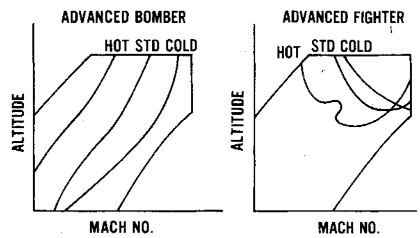

Fig. 2 Variation in control mode throughout the flight envelope.

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Control Methodology

State-of-the-art turbofans utilize very sophisticated controls along with variable geometry in the fan, compressor, and exhaust nozzle to achieve an optimum balance between performance and stability. Engines recently developed and now operating in an advanced fighter and in an advanced bomber represent two fundamentally different approaches toward mechanizing the technique for the attainment of this balance. The first employs speed control of both spools, relies heavily on average engine component performance, and indirectly infers fan operating point to assure adequate stability margin. The other employs a direct measurement of fan operating point to control the stability margin of the fan, controls fan speed to establish proper engine airflow and essentially lets the high spool float. A more definitive description of each control follows.

Advanced Fighter Control

The Advanced Fighter control establishes the fan and compressor speeds as a function of engine inlet total temperature. In general, the schedules which are programmed into the control are developed from a math model of the engine. One schedule which is determined external to the engine is the airflow-$T2$ schedule which is provided by the aircraft manufacturer. The purpose of this schedule is to optimize inlet performance by keeping the inlet and engine matched in airflow characteristics.

The nozzle area is modulated by the control to maintain the scheduled fan speed from which airflow can be inferred from an assumed operating line. The gas generator is controlled by main burner fuel flow. The demanded compressor speed is maintained until the turbine temperature limit is reached. The engine therfore is controlled to either a fan speed/core speed or a fan speed/turbine temperature limit mode.

Obviously, the ability of the programmed schedules to produce the desired fan operating line is dependent on the quality of the math model used in their derivation. It is noteworthy that, when real components differ (through degradation) and when extractions of bleed air and power are imposed on the engine, then the match point of the fan will migrate. Movement of the matchpoint is very significant and some discussion of how it should be handled will be provided subsequently.

Advanced Bomber Control

The Advanced Bomber control establishes the fan operating line through measurements of the total and static pressure at the fan discharge (so called "duct Mach number") as function of engine inlet total temperature. The fan operating line is in a closed-loop system in this control. Jet nozzle area is modulated to establish the desired fan operating line. Certain so called "topping" or overriding functions also exist in this control to assure safe operation: these being turbine blade metal temperature, burner pressure, and compressor speed. This approach toward establishing proper control schedules is less dependent on engine quality than the previously described one because the fan operating line is in a closed loop in the control with the gas generator left to float to maintain either scheduled fan speed or topping functions. Fuel flow is modulated to obtain the desired fan speed until either the burner pressure, compressor speed, or the turbine blade metal temperature limit is reached. Fuel flow then is cut back to maintain these limits. The fundamental advantage of this controls approach is that the fan operating line is essentially indepenent of engine quality, and performance does not suffer unecessarily by changes in component efficiencies.

Importance of Match Point

When real engine components deviate from those assumed for establishing control schedules or when an engine is tested under conditions far from those assumed for establishing control schedules or when an engine is tested under conditions far from the anticipated or "standard" condition, it is important that cycle and control aspects of the performance correction procedure be handled properly.

Deviation of real engine components from those assumed can alter the "match point" (fan operating pressure ratio and airflow) of a fan significantly from where it is desired to operate. This change in fan match point is most assuredly a change in the basic thermodynamic cycle of the engine, for the fan match point effectively determines the bypass ratio of the engine which, in turn, determines the accuracy of the thermodynamic cycle derivatives. Figure 3 depicts the fan match point migration for the advanced fighter engine with deterioration or under bleed and power extraction. Path 1-2-3 is that taken by the engine when controlled to core speed. Path 1-2′-3′ is the path taken when controlled to turbine temperature. Compensating schedules in the control are biased by burner pressure and desired turbine temperature characteristics to try and maintain the nominal (desired) operating line. Without these schedules, the engine match would remain at 2 or 2′. The degree and direction of match point migration depends upon the degree of deterioration or bleed/power extraction and the control mode of the cycle. In any case the derivatives (thrust vs T) obtained from a cycle deck which depicts the nominal engine (point 1) will differ from those of a real engine tested with its match point at either 3 or 3′.

Figure 4 displays the fan match point migration for the advanced bomber control under the same deterioration of customer extraction conditions. Point 1 describes the initial engine match point for a nominal engine. When bleed or power is extracted from the engine or when engine components deteriorate, the engine either will maintain the match point at 1 with an increase in fuel flow or will rematch to point 2 if the turbine temperature limit is reached with a corresponding rollback in fan speed. In both cases, the desired engine operating line is maintained. Derivatives obtained with the math model matched at point 1 will be accurate for the real engine as long as the turbine temperature limit is not reached. This contrasts with the advanced fighter engine's control which cannot maintain matchpoint under either control mode and does not maintain operating line when match point can no longer be held.

A second and even stronger consideration in choosing an appropriate data correction methodology is the migration of engine match point because of nonstandard engine inlet temperature test conditions. Figure 5 shows the migration of the fan operating point because of nonstandard inlet temperature for the advanced bomber control. The match point migration in this case and the engine thrust lapse characteristics with T are caused entirely by the control schedules as they vary with T. Derivatives obtained with the math model in this case

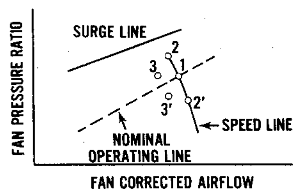

Fig. 3 Fan operating point: migration with deterioration or bleed and power extraction (advanced fighter).

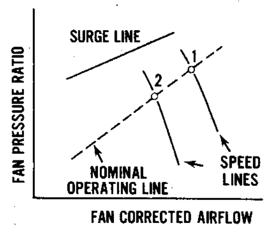

Fig. 4 Fan operating point: migration with deterioration or bleed and power extraction (advanced bomber).

would be accurate because both the fan speed and operating line (fan duct $\Delta P/P$) which determine the migration are measured directly and set by the control. The same match point migration occurs for the advanced fighter engine with nonstandard inlet temperatures. However, it is not as straightforward as for the advanced bomber because the operating line is not measured (it is only inferred from the engine rotor match), and the airflow scheduled is biased by compensating schedules as engine component quality varies. Figure 6 shows the basic schedules in the advanced fighter control that vary with engine inlet temperature.

The derivative obtained with the math model for this change in T can expect to vary somewhat from the real engine because the operating point migration is inferred and not measured as in the advanced bomber control. The math model would have to duplicate the real engine exactly in all engine component performance characteristics for this to occur.

The foregoing discussion concerns only changes in the control schedules with nonstandard inlet temperatures when the engine is operating entirely on the speed control mode. Difficulty also arises in choosing an exact data correction methodology when the turbine temperature limit is reached somewhere between the tested and desired T. Figure 7 illustrates this problem schematically. The figure shows the theta-break occurring at a different T than in the real engine. Again, model and engine component characteristics would have to be identical for the break point to occur at exactly the same T, and this never is the case. Therefore, in this situation large errors can occur in the derivatives obtained by the math models and special attention must be made in this case.

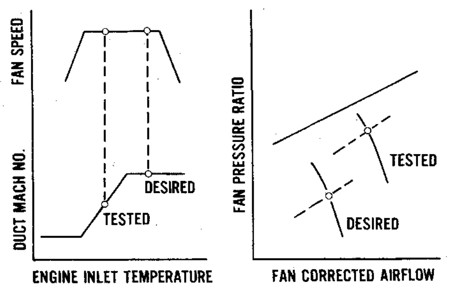

Fig. 5 Fan match point: migration for nonstandard inlet temperatures (advanced bomber).

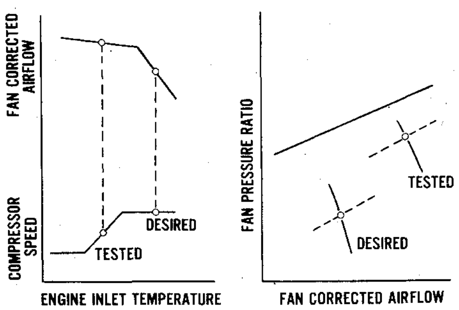

Fig. 6 Fan match point migration for nonstandard engine inlet temperature (advanced Fighter).

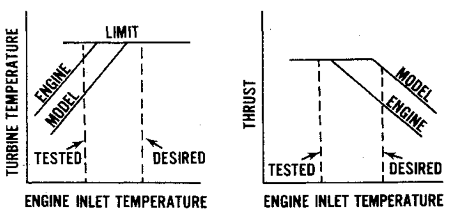

Fig. 7 Illustration of performance correction problem.

Engine Trim and Control Trim Bands

In the real world the desired operating line, as set by the control schedules and logic, is maintained within a given amount of variance about a nominal value. This variance is set by the fact that it is easier to trim the engine into an operating band than to a given point. The width of the band usually is set by an upper bound established by stability criteria and a lower bound by minimum specification performance. Therefore, the engine's thrust characteristics will vary from the nominal engine by the width of the trim band. This is shown schematically in Figure 8.

Technical Approach

Math models, programmed for the digital computer, are used extensively today to solve for the effects of performance related changes to engines. These math models have been refined to such a level of sophistication that they can be used to evaluate effects far too small to evaluate in an actual test. Accordingly, a math model representing each engine was used to study the performance correction methodology outlined herein. Performance characteristics were established for a baseline configuration known as a status engine. A status engine model or "status deck," as it is commonly referred to, generally is used to predict performance or to "correct" performance from a nonstandard to a standard condition. The procedure used to determine the errors is as follows: 1) using the status deck, generate the data needed for the performance correction model; 2) adjust either control schedules or cycle efficiencies to represent a nonstatus engine and generate the resulting performance characteristics; 3) using the performance correction models, correct the nonstandard data determined in 2) to standard data; and 4) knowing the true standard, calculate the error introduced by the performance correction model.

It is worth noting that, for the purpose of this analysis, the characteristics of the "nonstatus" engines were known throughout the range of interest and, therefore, the error in corrected thrust using each of the performance correction models could be determined. This situation is distinguished from the real world cases where the characteristics of a particular engine (nonstatus) are known only over a very narrow range of conditions.

Certain functional relationships were assumed to exist between the baseline and the modified math model. Recall that the baseline represents the status engine and the modified math model represents a particular engine having similar characteristics but differing in some significant manner, i.e., different component efficiencies or control schedules. The functional relationships assumed can be described verbally as follows: a) an inferred functional relationship between thrust and independent variables-subsequently handled through a Taylor series expansion, b) similar to a), except that, in the course of the derivation, an additional approximation is applied which leads to a correction procedure which is multiplicative in nature, c) a functional relationship is assumed which applies adders to the nonstandard day thrust to obtain standard day thrust, and d) a functional relationship is assumed which asserts that the ratio of test day thrust to standard day thrust is essentially constant for a wide variation in engine quality or control schedules.

To simulate a nonstatus engine the changes shown in Table 1 were made to the status deck. These changes are realistic

Fig. 8 Typical trim band.

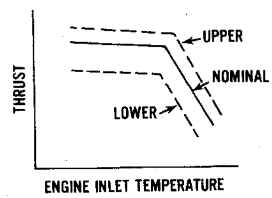

Table 1 Changes to baseline math model to simulate engine variations

	Advanced fighter control	Advanced bomber control
Control change	Core speed + 28 Turbine inlet Temperature + 14	Duct mach number − 0.02 Turbine temp − 25 Fan speed + 40 rpm
Cycle change	High turbine efficiency − 0.01	High turbine efficiency − 0.01

and, if anything, are conservative. The control schedule changes are based on the trim band width plus the control dead band width for both the Advanced Fighter and Advanced Bomber Control. The component change of 1% is consistent with allowable clearances in manufacturing and observed variations in turbine performance from highly instrumented test engines.

Assumptions Made for Performance Correction Model

Since the math model of an engine forms the basis for evaluating the quality of performance correction methodology, it is appropriate to discuss the possible relationships between any given engine and the math model. Clearly, if the math model perfectly represents an engine then, as long as the two are handled consistently, perfect correction can be expected. Other relationships can be described as follows.

In general, the functional relationship between a particular engine and its math model could be more or less arbitrary. However, by analytically examining those aspects of the engine that account for the engine-to-math-model differences one can determine whether the differences are predominately in slope or level. In the most complex case we are able to consider where, over one range or independent variable, slope differences predominate whereas, over another, level differences predominate. Where control schedules are shifted upward or downward one can expect that the thrust level of the engine essentially will be shifted in a similar manner. When changes to component efficiencies or parasite flows occur, these more directly affect tthe thermodynamic cycle and thus the thrust-T relationship or slope, at the test point, wheras the control schedules will dominate the correction from the test day to the standard day point.

Taylor Series Expansion

In general,

$$F=f(p,P/p,T) \tag{1}$$

for an engine operating at a fixed power setting; p describes the altitude at which the engine is operating. P/p describes the Mach number at which the engine is operating, and T is assumed to be the primary independent control parameter which is sensed. A Taylor Series Expansion of the Eq. (1) results in the following:

$$Fs=Fx+\frac{\partial F}{\partial p}\Big|_x\{(p)_s-(p)_x\}$$
$$+\frac{\partial F}{\partial(P/p)}\Big|_x\left\{\left(\frac{P}{p}\right)_s-\left(\frac{P}{p}\right)_x\right\}$$
$$+\frac{\partial F}{\partial T}\Big|_x\{(T)_s-(T)_x\}+\ldots \tag{2}$$

Where $|_x$ denotes that the partial derivative is evaluated at a nonstandard condition x. The subscript s denotes that the quantity in parentheses is evaluated at standard conditions. It also is asserted that the partial derivatives are independent of changes in other variables, e.g., $\partial F/\partial p$ is independent of the value of P/p and T. Terms beyond the first in the Taylor series have not been considered because of the associated complexity.

Since this paper is control oriented, we will consider only that the variable which is sensed by the control for illustrations of the method. Accordingly, the relationship becomes, in finite difference form.

$$F_s=F_x+(\partial F/\partial T)|_x(\Delta T)_s \tag{3}$$

where

$$(\Delta T)_s=T_s-T_x \tag{4}$$

The partial derivative is a function of the temperature at which it is evaluated and can be determined by numerically calculating $\partial F/\partial T$ at several values of temperature.

Utilizing these values of the partial derivative, one then can calculate the standard day thrust which would result utilizing the Taylor series expansion method. Subsequently, the error introduced by this method can be computed. The error is defined as the difference between the calculated standard day thrust using the performance correction model and the "truth" which is known from running the nonstatus math model at the standard day condition. Theses errors were calculated for nonstatus engines to evaluate both control schedule changes and cycle changes. Figures 9 and 10 graphically depict the results of the error calculations.

Log Series

It was shown in the previous section that the general functional relationship between thrust and its determiners can be expanded via a Taylor series. The end product of this expansion was an expression which was additive in nature. If one desires to utilize a final expression which is multiplicative in nature, then it can be assumed that thrust is a function of the logarithm of its independent variables.

If the general functional relationship of Eq. (1) exists, then the functional relationship

$$F=F[(\ln p,\ln(P/p),\ln T)] \tag{5}$$

also exists. Now, a Taylor series expansion of this expression is

$$\ln F_s=\ln F_x+\left\{\frac{\partial\ln F}{\partial\ln p}\right\}_x[(\ln p)_s-(\ln p)_x]$$

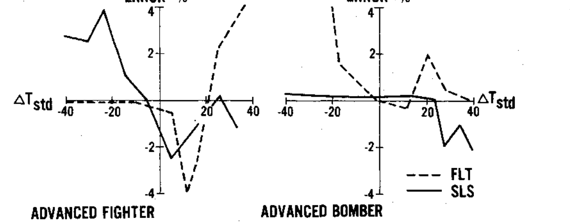

Fig. 9 Errors associated with control schedule changes: Taylor series.

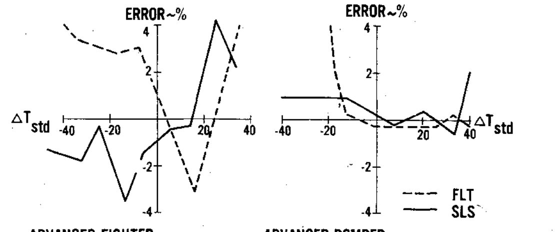

Fig. 10 Errors associated with degraded engine: Taylor series.

$$+\left\{\frac{\partial(\ln F)}{\partial(\ln P/p)}\right\}_x\left[(\ln\frac{P}{p})_s-(\ln\frac{P}{p})_x\right]$$

$$+\left\{\frac{\partial(\ln F)}{\partial(\ln T)}\right\}_x\left[(\ln T)_s-(\ln T)_x\right]+\ldots \tag{6}$$

Using both sides of the equation as a power of e and recalling

$$e^x=1+x+(x^2/2!)+(x^3/3!)+\ldots \tag{7a}$$

$$F_s=F_x\left[1+\frac{\partial(\ln F)}{\partial(\ln p)}\Big|_x(\Delta\ln p)_s\right]$$
$$\times\left[1+\frac{\partial(\ln F)}{\partial[\ln(P/p)]}\Big|_x(\Delta\ln\frac{P}{p})_s\right]$$
$$\times\left[1+\frac{\partial(\ln F)}{\partial(\ln T)}\Big|_x(\Delta\ln T)_s\right] \tag{7b}$$

which can be written in finite difference form as

$$F_s=F_x\left\{1+\left[\frac{\partial F/F}{\partial p/p}\right]_x(\Delta\ln p)_s\right\}$$
$$\times\left\{1+\left[\frac{\partial F/F}{(\partial P/p)/(P/p)}\right]_x(\Delta\ln\frac{P}{p})_s\right\}$$
$$\times\left\{1+\frac{\partial F/F}{\partial T/T}\right]_x(\Delta\ln T)_s\right\} \tag{8}$$

Considering only the change in T the expression can be simplified to

$$F_s=F_x\left\{1+\left[\frac{\partial F}{\partial T}\frac{T}{F}\right]_x\ln\left(\frac{Ts}{Tx}\right)\right\} \tag{9}$$

To evaluate this expression numerically the term

$$KT=1+\left[\frac{\partial F}{\partial T}\frac{T}{F}\right]_x\ln\frac{Ts}{Tx} \tag{10}$$

is calculated over the range of T of interest. Using the status deck the expression can be calculated in a manner similar to the way derivatives were calculated in the Taylor series development.

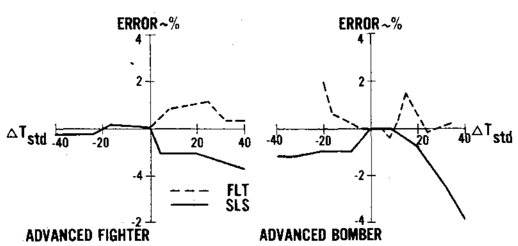

Fig. 11 Errors associated with changes in control schedules: additive method.

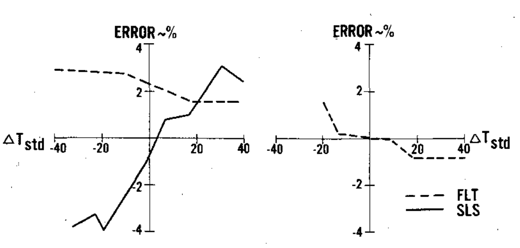

Fig. 12 Errors associated with degraded engine: additive method.

Then one can calculate the error in standard day thrust which would result utilizing the log series model. Since the results of the calculations were nearly identical to those of the Taylor series they are not presented.

Additive Method

Considering that the performance correction model is of form

$$F_s=F_x+\Delta F(p)_x+\Delta F(P/p)_x+\Delta F(T)_x \tag{11}$$

consistent with other developments in this paper we will consider only the effect of variations in T. Furthermore, in the development the adjustment to thrust is treated as an adder onto the test day thrust to obtain standard day thrust. Now, using the modified math model to represent an engine with different controls schedules and different cycle efficiency, the error curves depicted in Figs. 11 and 12 can be generated.

Multiplier Method

One also could assert that a performance correction model of the following form is valid:

$$F_s=F_x\{F(p)_x F(P/p)_x F(T)_x\} \tag{12}$$

where the terms $F(p)_x$, $F(P/p)_x$, $F(T)_x$ are, respectively, the ratio of the standard day thrust to the thrust at condition x due to ambient pressure, ram and temperature, Again, only the variation in temperature will be considered in illustrating this method. Using the math model, the thrust multiplier can be determined and subsequently used to "correct" non-standard data. The thrust multiplier is defined as Fs/Fx. Now, using the same modified math model as was done for previous developments, error curves can be generated. Since the results of these calculations were quite similar to those of the Additive Method they are not presented.

Classical Method

Most propulsion textbooks present a short treatise on dimensional analysis and how it can be used to calculate dimensionless or paradimensionless groups of variables which then allow one to infer engine performance over a wide range of conditions based on only a few test points. However, it is the authors' experience that the utility of this method is reduced greatly when considering engines which have large variations in jet nozzle area. Furthermore, the inability of the industry to devise a simple, yet accurate, means of measuring jet nozzle area greatly complicates the actual calculation of accurate representative dimensionless groups. And finally, all treatments of dimensional analysis as applied to turbine engines do not consider how changes in control mode must be handled. In other words, jet nozzle area may be modulated to obtain one value of, say, fan speed over one range of engine inlet temperatures and differently to obtain another value of fan speed over another range of engine inlet temperatures. Thus, where the traditional dimensional groups for thrust are

$$\frac{F}{AP}=f\left(\frac{N\sqrt{A}}{\sqrt{\Theta}}\right) \tag{13}$$

one would expect at least one more dimensionless group and consequently the expression would be

$$\frac{F}{AP}=f\left(\frac{N_1\sqrt{A}}{\sqrt{\Theta_1}},\frac{N_2}{\sqrt{\Theta_2}}\right) \tag{14}$$

For an engine which has fixed nozzle areas but variable stators and/or guide vanes in the compressor, it is still satisfactory to use dimensionless parameters to generalize performance data. This is because the variable geometry changes vary consistently with correct speed and not independently.

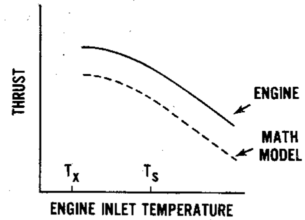

Fig. 13 Relation of thrust and inlet temperature in engine and math model.

Conclusion

Errors in correcting engine performance data to conditions different from those tested can be attributed to the difference between the baseline math model and the engine and to shortcomings in the correction model itself. Of the four performance correction models described in this paper, errors in the first two (i.e., Taylor series expansion and log series expansion) are caused first of all by errors in the performance correction model itself and second by differences between the baseline math model and the engine. Errors in the remaining two models (i.e., the Additive and Multiplicative) are caused by differences between the baseline math model and the engine. This can be illustrated further by considering that, if the math model is a perfect depiction of the engine, then both the Additive and Multiplicative methods will correct engine data perfectly, whereas the Taylor and Log series expansion will not, since they are approximations of a functional relationship. This approximation results, of course, from dropping all the higher-order terms in both the Taylor and Log series expansion and in addition, applying the series approximation for e^x in the log series.

Clearly then, it would appear that the Additive and Multiplicative methods are, in general, more desirable models than either the Taylor or Log series methods. The next question to be addressed is that of which of the two, Additive or Multiplicative, is a more desirable performance correction model. There is some theoretical inspiration for considering that the Additive method is more desirable than the Multiplicative method. The Additive method is tantamont to the Taylor series expansion considering *all* terms in the series expansion rather than just the first two. To illustrate this, consider the two equations below:

$$F_s = F_x + \frac{\partial F}{\partial T}\Big|_x \Delta T_x + \frac{\partial^2 F}{\partial T^2}\Big|_x \frac{\Delta Tx^2}{2!} + \frac{\partial^3 F}{\partial T^3}\Big|_x \frac{\Delta Tx^3}{3!} + \ldots \quad (15)$$

$$F_s = F_x + \Delta F(T)_x \quad (16)$$

The first equation is the Taylor series expansion method and the second is the additve Method. For a perfect math model it is apparent that the additive term is equal to all the Taylor series expansion terms. However, the real significance to be noted here is that the Additive correction model will correct performance data perfectly if the derivatives of the engine are the same as those of the baseline math model. The mulplicative method, however, requires not only that the derivatives be identical, but that the level of thrust be equal to that of the performance correction model. This is illustrated in Fig. 13 where thrust is plotted against engine inlet temperature. It is assumed in the figure that the engine and math model differ in thrust by a fixed amount across the range of interest.

The multiplicative correction model, you will recall, is written as

$$F_s = F_x \, (Fs/Fx)_{\text{mm}} \quad (17)$$

where the subscript mm denotes that the quantity in parentheses is determined from the math model. It is apparent that since the levels of thrust differ by a constant amount at each value of temperature then the assumption implied by the equation is true only if that constant amount is zero.

Thus, where those differences between the baseline math model and the engine are primarily in level of thrust (which might be due to, say, fan speed schedule differences) one could expect that the Additive method would be most satisfactory. When the differences are due to cycle changes, one would expect derivatives to change since they are of course dependent only on the thermodynamic cycle.