AD-A100 030 RAND CORP SANTA MONICA CA F/G 1/3
PERFORMANCE ADVANCES IN FIGHTER AIRCRAFT: MEASURING AND PREDICT--ETC(U)
JUL 80 W L STANLEY
UNCLASSIFIED RAND/P-6500 NL

1 OF 1
AD A
100030

END
DATE
FILMED
7-81
DTIC

LEVEL II

(4)

AD A100030

PERFORMANCE ADVANCES IN FIGHTER AIRCRAFT:
MEASURING AND PREDICTING PROGRESS

William L. Stanley

July 1980

RAND/P-6500

PERFORMANCE ADVANCES IN FIGHTER AIRCRAFT:
MEASURING AND PREDICTING PROGRESS*

William L. Stanley

July 1980

*Originally prepared for presentation at the AIAA Aircraft Systems Meeting, Anaheim, California, August 4-6, 1980.

PERFORMANCE ADVANCES IN FIGHTER AIRCRAFT: MEASURING AND PREDICTING PROGRESS

William L. Stanley*
The Rand Corporation
Santa Monica, California

Abstract

A new approach has been developed for measuring advances in jet fighter air vehicle performance. The approach recognizes the multiparameter tradeoffs imposed by the development process by simultaneously considering trends in a number of performance areas, rather than treating each area separately. Relationships are established between the time of appearance of an aircraft design and such parameters as specific power, sustained load factor, Breguet range, and payload fraction. Using the approach to project where the current acquisition environment is leading us with respect to fighter performance suggests that (1) U.S. fighter air vehicle performance is presently advancing at a diminishing rate, (2) increasing the rate of advance may be costly, and (3) performance growth opportunities offered by derivative aircraft seem limited. The results raise some questions about the most desirable mix of investment in air vehicle, avionics, and armament technology.

I. Introduction

The process of formulating realistic and achievable air vehicle performance goals for future fighter aircraft involves considerable uncertainties for the military aviation planner. Usually his decisionmaking base includes the demonstrated performance of past and present fighters designed to meet a variety of mission requirements, assessments of progress in disparate individual technology areas, and the expectations of airplane manufacturers about how they can integrate the individual technological advances into actual flight hardware. Using this and other information, the planner tries to arrive at an appropriate mix of emphasis on air vehicle, avionics, and armament performance in specifying his service's requirements. The expectation of a particular level of performance should carry with it an acknowledgment of the amount of technical risk associated with developing a vehicle having that performance. Although wider considerations sometimes dictate otherwise, that perceived risk should influence the structure of the development program (e.g., a program with considerable technical risk might include a prototype demonstration while a low-risk program might move directly to a vehicle having a near-operational configuration).

Obviously, misinterpretation of the levels of technical risk can and has led to inappropriate structuring of major weapon system acquisition programs, often to the detriment of cost, schedule, and performance goals. With today's intense competition for defense resources, and the lower rate of introduction of new fighter aircraft, the consequences of misinterpreting risks assume greater importance. In this context, it seems particularly desirable to have a varied portfolio of techniques with which to assess the reasonableness of fighter performance goals for the future. The fact that misinterpretations still happen today provides ample justification for striving to develop new innovative approaches.

This paper describes the development and application of a new approach for measuring the performance consequences of advances in fighter air vehicle technology that complements other techniques used for assessing trends in performance advance. It focuses on performance advances demonstrated by the fighter air vehicle--that is, the basic platform of airframe, engine, and associated subsystems which operate as a unit to perform basic aircraft maneuvers. It does not quantify trends in the development of avionics and armament systems. By using the analytical framework of the approach, the paper retrospectively examines the rate of fighter air vehicle performance advance achieved in the past and draws inferences about the kind of performance advance we might expect to achieve in the future, if the essential features of the contemporary development environment persist.

II. Approach for Measuring Performance Advances

Development of Approach

Past research successfully developed a quantitative technique for measuring technological advance in aircraft turbine engines.[1] Retaining the essential features of that approach, subsequent research has extended its application to the fighter air vehicle as a whole. While a detailed exposition on the development of the approach is reported elsewhere,[2] we will try to highlight some of its more salient features here before illustrating its applications.

To measure the rate of performance advance required the development of quantitative expressions that characterized the level of air vehicle performance and provided a temporal measure of when the performance was achieved. The fact that designers frequently trade off performance in one area (e.g., combat) to satisfy mission requirements in another area (e.g., cruise) pointed to the desirability of having a quantitative framework that simultaneously considered the multiparameter tradeoffs imposed by the development process, rather than considering trends in each performance area separately. That led to an expression having the form:

$$t = f(P_1,\ldots,P_n)$$

with t the time when a particular jet fighter aircraft appeared and the Ps the set of n performance parameters describing the overall level of performance of the aircraft.

Specification of the equation's functional form and a determination of its coefficients provide a

* Associate engineer, Engineering and Applied Sciences Department

way to measure the average rate of performance advance over time. One can assess the reasonableness of performance expectations for a prospective program by comparing the rate of performance advance required to satisfy program goals with the empirically established rate of advance quantified by the expression. To do so, one uses the parameter values describing a fighter aircraft concept and the equation to calculate a time of appearance based on past trends. If the schedule expectation of the service or contractor is significantly earlier than that suggested by the trend, then one might more critically assess the ambitiousness of the performance goals.

To identify an appropriate set of parameters for consideration, we began by surveying the major technological innovations introduced in jet fighter air vehicles during the past thirty years. The survey suggested that in introducing most of these innovations, designers had as a goal the improvement of performance in four major areas: (1) speed, acceleration, (2) maneuverability, (3) cruise efficiency, and (4) payload carriage. On this basis, we assembled the candidate set of parameters shown in Table 1 to measure performance in the four major areas and a few others as well. Although data collection difficulties certainly shaped the constitution of the parameter set, it did meet our desire to encompass some of the major cruise and combat parameters the designer trades off to satisfy mission requirements.

No completely unambiguous benchmarks exist to indicate when a particular level of performance has been achieved. After considering several alternatives, we elected to use first flight date, generally, although not exclusively using the first flight date of the development test aircraft, since it usually establishes basic air vehicle performance and includes most of the fully engineered systems for the production vehicle. Because the sequence of fighter aircraft development has varied from program to program, we could not always consistently apply this rule, and hence, had to make some subjective decisions about appropriate first flight dates for some of the aircraft.

One additional important aspect in the development of the approach involved identifying the most appropriate equation form. The equation form is of more than just mathematical interest, since different forms imply different rates of performance advance (e.g., deceleration, constant, acceleration). We evaluated various logarithmic and linear expressions in the dependent variable and the independent variables to cover a spectrum of possibilities.

Applying tests for intuitive engineering reasonableness, statistical quality, and predictive properties, we estimated the performance trend expressions shown in Table 2 from a sample of 25 Air Force and Navy jet fighter aircraft developed since the mid-1940s. The log-linear expressions each have two variables describing performance in the combat arena and two describing performance in getting to the combat arena. Specific power, the power per pound the air vehicle develops, used by Gabrielli and von Karman in a landmark paper long ago,[3] provides a crude measure of speed and acceleration capability. Sustained load factor directly measures maneuverability. The carrier capability variable corrects for differences

General Performance Attributes	Parameter
Combat	
Speed, altitude performance, energy, acceleration	Maximum speed
	Maximum specific power
	Maximum specific energy
	Maximum climb rate (sea level)
	Combat ceiling
Maneuverability	Maximum sustained load factor (M = .8, h = 25 kft)
	Thrust-to-weight ratio (sea level)
	Wing loading
Cruise	
Range, payload	Breguet range factor
	Internal fuel fraction
	Total fuel fraction (internal and external)
	Payload fraction
	Useful load fraction
	Breguet range
	Payload fraction x Breguet range
Other	
Structural strength	Structural efficiency
Weight	Empty weight
Miscellaneous	Carrier capability
	Variable geometry
	Speed class
	Mission
	Manufacturer
	Design lag
	Design antecedent
	Design class

Table 1 Fighter Air Vehicle Performance Parameters

in the characteristics of land- and sea-based fighters. The remaining parameters, in various ways, measure cruise efficiency and payload carriage capability.

The equations seemingly exhibit excellent explanatory powers, but do have some weaknesses. Limitations in the descriptive power of their variables and the sizable standard errors of estimate make them unsuitable for making subtle distinctions between similar fighter designs. The small sample size contributes to some instability in the equations and the importance of the propulsion system in determining combat performance contributes to higher than desirable levels of correlation between specific power and sustained load factor. It seems likely that the inevitably small sample of jet fighter aircraft, the uneven distribution of their first flight events through time, and a historically broad definition of what constitutes a fighter aircraft will make it extremely difficult to significantly improve the precision and descriptiveness of these expressions. Despite these shortcomings, considerable testing has indicated that the expressions can still play a useful role in measuring gross trends in performance.[2]

Table 2 Performance trend expressions for fighter aircraft

	R^2	SEE	F
(1) $\ln(t) = 3.878 + .065 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + .406 \left[\frac{\text{Breguet Range}}{1000} \right] + 1.409 \left[\frac{\text{Sustained Load Factor}}{10} \right] + .939 \left\lvert \text{Payload Fraction} \right\rvert - .093 \left\lvert \text{Carrier Capability} \right\rvert$	.945	.117	65.8
(.001) (.00001) (.001) (.020) (.100)			
(2) $\ln(t) = 3.643 + .072 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + 1.257 \left[\frac{\text{Breguet Range Factor}}{10{,}000} \right] + 1.184 \left[\frac{\text{Sustained Load Factor}}{10} \right] + .876 \left[\text{Internal Fuel Fraction} \right] - .105 \left\lvert \text{Carrier Capability} \right\rvert$	.938	.125	57.2
(.0001) (.010) (.005) (.005) (.100)			
(3) $\ln(t) = 3.530 + .059 \left\lvert \frac{\text{Thrust} \cdot \text{Vmax}}{100\, W_{cbt}} \right\rvert + 1.768 \left[\frac{\text{Breguet Range Factor}}{10{,}000} \right] + 1.186 \left[\frac{\text{Sustained Load Factor}}{10} \right] + .526 \left[\text{Total Fuel Fraction} \right] - .168 \left\lvert \text{Carrier Capability} \right\rvert$	.922	.140	45.2
(.005) (.001) (.010) (.050) (.020)			

NOTES: t=calculated first flight date measured in months since January 1, 1940.
Each equation is based on 25 observations and has 5 and 19 degrees of freedom.
Upper bound for risk of incorrectly rejecting the null hypothesis that a coefficient is really zero is shown in parentheses below the coefficients.
Thrust measured in pounds, Vmax in knots, combat weight in pounds.
Carrier capability variable: 1 denotes no capability, 0 denotes capability.
SEE of .117 around mean first flight date in sample corresponds to + 21.9, - 19.4 months.

Fig. 1, a graphical representation of Eq. (1), introduces the aircraft in the sample and by showing the distribution of the data points about the 45 degree line provides one measure of how well the equation fits the sample. The vertical axis measures the calculated first flight date obtained by inserting aircraft parameters in the equation, and the horizontal axis the actual first flight date. The scatter of the data points should serve as a reminder that the residuals represent all those unquantified factors that influence the first flight date of an aircraft including technological factors not covered by the independent variable parameter set, scheduling decisions, congressional and service funding decisions, development philosophy, etc. The approach treats such factors only implicitly.

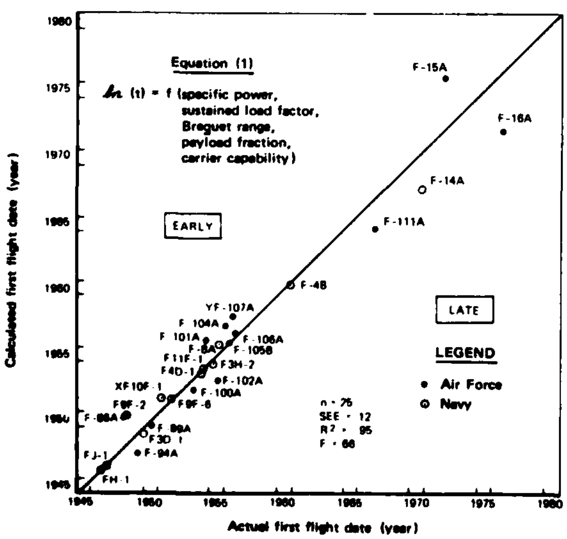

Fig. 1 Multivariable performance trend for fighter aircraft

III. Expectations For Performance Advances in the Future

Performance Growth Through Derivatives

The development of new aircraft represents a direct means to introduce new technology, but the increasing costs of fighter aircraft have reduced their rate of introduction. Modifying existing designs to develop derivative aircraft has represented an alternative means for incrementally introducing new technology. But can derivatives approach the performance advance rate for new aircraft? How much difference can a new engine make to the performance improvement exhibited by a derivative aircraft?

We hypothesized that a designer would find it more difficult to improve performance when working within the constraints of an existing design. To test that hypothesis, we used the performance trend established by Eq. (1) and examined the rate of performance advance exhibited by some derivative designs of those aircraft in our sample that established the average growth rate for new designs. Substituting the characteristics of the derivative aircraft into Eq. (1), we plotted in Fig. 2 their position relative to their predecessor aircraft. To assess relative rates of performance advance, we compared whether the slopes of the performance advance lines connecting derivative and predecessor aircraft were greater than or less than the average performance advance rate for new designs, which in this format is represented by the 45 degree line.

The average rate of performance advance for the sever. derivative aircraft incorporating new engines (i.e., different than those in the predecessor aircraft) almost matched the rate for new designs. The thrust of the new engines incorporated in these predominantly 1950s aircraft on average exceeded that of the engine in the predecessor model by 70 percent. Given current engine options, these rates of thrust improvement seem less likely today.

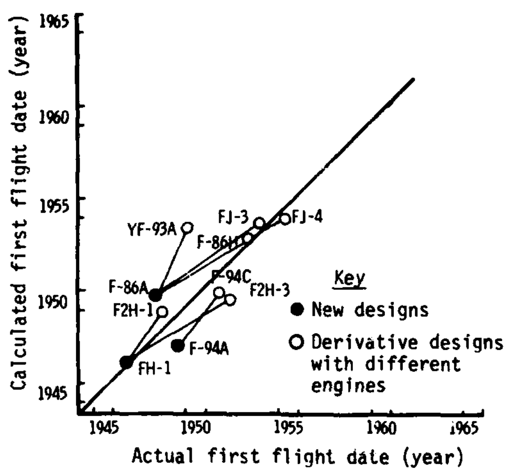

Fig. 2 Performance growth for derivatives with different engines

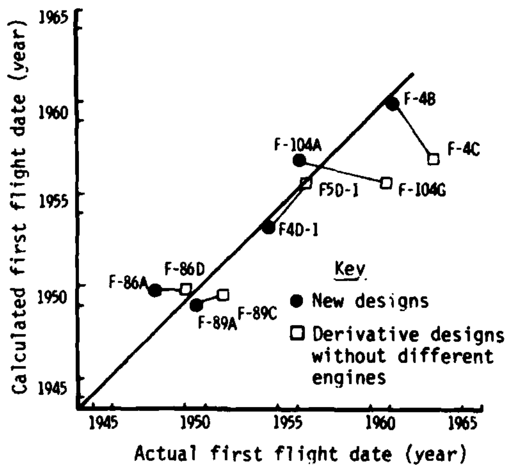

Fig. 3 Performance growth for derivatives without different engines

Results were quite different for those derivative aircraft that did not incorporate engines different from those of the predecessor model. In this case, Fig. 3 indicates average air vehicle performance growth was negligible when measured in terms of the parameters of Eq. (1), while average thrust increases derived from product improvements of the original engines measured 12 percent.* *These results prompt two observations.* First, they reinforce the importance of the propulsion system in establishing the rate of performance advance. Second, it seems unlikely in today's environment of engine options that derivative aircraft will often match the rate of air vehicle performance advance achievable by a new design. Nonetheless, enhancements in operational performance offered by advancements in avionics or armament technology, or more subtle yet valuable improvements in air vehicle performance than those quantified by Eq. (1) may still offer considerable justification for the development of derivative aircraft.

The Rate of Performance Advance Through Time

Does the rate of air vehicle performance advance today differ appreciably from the rate achieved during the 1940s and 1950s? If so, what does that portend for future fighter developments? To address these questions, we have constructed Fig. 4, in which the logarithm of the calculated first flight date, the left side of performance trend Eq. (1), is plotted against the actual first flight date for each aircraft in the sample. The solid line passing through the data points (analogous to the 45 degree line in previous figures) represents the average rate of performance advance. In this context, the vertical axis serves as an index of performance. For present purposes the numbers are not important—only that movement in the vertical direction connotes performance advance.

For the overall 30 year period, we see a decline in the rate of air vehicle performance advance when measured in terms of the parameters of Eq. (1). Today we would regard the jet fighter air vehicle *as a maturing technology.* When considering only the trend established by aircraft developed through the F-104A, America's first operational Mach 2 fighter, a separate analysis indicated that performance had at least advanced at a constant rate and perhaps even accelerated. Many new designs were introduced during this period as designers sought to exploit new innovations spawned by World War II, the Korean conflict, and the onset of the Cold War. We suspect, but do not have enough data points to fully quantify, that the performance advance curve for jet fighters is probably following the classical "S" shaped curve characteristic of so many other technologies.

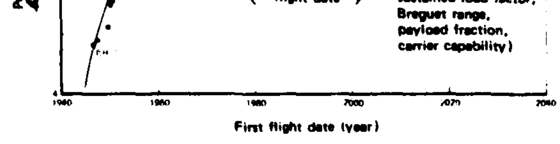

Fig. 4 Performance advance through time

*In Fig. 3, the F-4C has a lower performance index rating (i.e., calculated first flight date) than the F-4B, primarily because it did not retain a carrier capability.

The end of the Century Series appears to represent a watershed of sorts in terms of a marked change in the rate of performance advance. For a complex set of reasons which we have not yet completely sorted out, including technical limits, cost constraints, and changing requirements, performance is improving at a slower rate now than in the 1950s.

Without some fundamental breakthroughs, not unlike the introduction of turbojet propulsion, it seems unlikely that we can expect a return to the rates of performance advance achieved during the 1950s, at least when performance is measured in terms of the parameters of Eq. (1). An extrapolation of present trends shown in Fig. 4 suggests that at the 90 percent confidence level it might take two to five times longer to make an absolute improvement in F-15A air vehicle performance comparable to that made in going from the F-4 to the F-15. Incidentally, we believe the considerable uncertainty associated with this projection is not only a product of the uncertainty of the approach itself but also of the development process. In any case, this projection raises some provocative questions about whether we have as much leverage in the air vehicle performance area as we once had.

Trends in Fighter Airframe and Engine Costs

Some might suggest that a relaxation in cost constraints could increase the slope of the performance advance curve in Fig. 4. Certainly some contemporary fighter development programs like the F-16 and F-18 have made modest performance sacrifices to reduce costs. Quantifying the role of cost in shaping the performance advance curve remains a highly desirable but as yet unachieved objective, although some of the trends in fighter airframe and engine costs do suggest a linkage. For example, in terms of airframe program costs per pound, Fig. 5 illustrates the rapid rate of increase in costs that occurred during the introduction of the Century Series, which paralleled the period of rapid performance advances. The rate of increase in airframe costs per pound has become decidedly more measured for subsequent Mach 2 developments, as has the rate of performance advance. Similar, although less persuasive cost trends are depicted in Fig. 6, which illustrates the rate of increase in fighter engine program costs per pound of thrust. If indeed cost is one of the major factors constraining air vehicle performance advance, can we afford to increase the rate of advance today, even if nothing else stymies us?

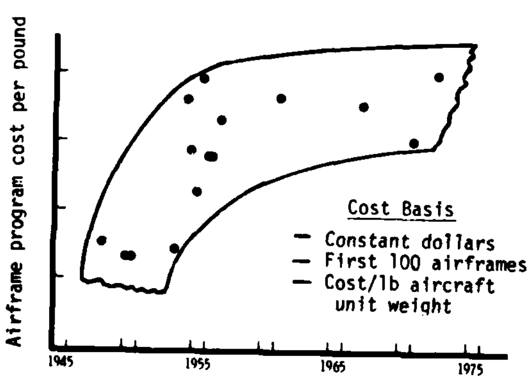

Fig. 5 Fighter airframe cost trend

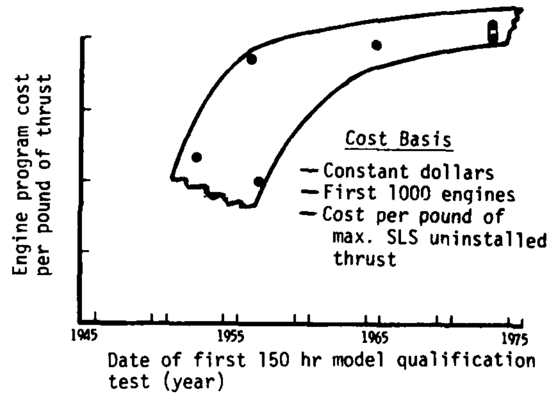

Fig. 6 Fighter engine cost trend

IV. Observations

When expressing fighter air vehicle performance in terms of speed/acceleration, maneuverability, cruise efficiency, and payload carriage, we see a decline in the rate of advance when measured against the rate of progress achieved through the mid-1950s. As we have reached higher and higher plateaus of air vehicle technology, sustaining the rate of performance improvement has become more and more difficult. If we continue to place a high value on achieving air vehicle performance advances in the areas noted above, then the emerging trend in the extended amount of time required to improve performance should perhaps be the source of some concern.

Whether we will have to accept a decline in the rate of performance advance will depend on a multiplicity of factors that influence the development process, including cost and technical constraints, changing requirements driven by perceptions of the threat, and the attitudes and responsiveness of the institutions involved in fighter aircraft development. Certainly, in future fighter developments, the military aviation planner will have to carefully balance emphasis on improvements in engine and airframe technology against improvements in other technologies such as avionics and armament that may at times provide easier avenues for enhancing combat effectiveness.

References

1. Alexander, A. J., and J. R. Nelson, Measuring Technological Change: Aircraft Turbine Engines, The Rand Corporation, R-1017-ARPA/PR, June 1972.

2. Stanley, William L., and Michael D. Miller, Measuring Technological Change in Jet Fighter Aircraft, The Rand Corporation, R-2249-AF, September 1979.

3. Gabrielli, G., and T. H. von Karman, "What Price Speed?--Specific Power Required for Propulsion of Vehicles," Mechanical Engineering, Vol. 72, No. 10, October 1950.

DATE
ILME