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Engine–Airframe Integration During Conceptual Design for Military Application

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Conceptual design has critical leverage on the entire course of design processes because it addresses the issue of selecting the baseline design to optimally accomplish the specified set of requirements. Conceptual-design software has been developed to determine the optimal engine–airframe match over a given mission role, its multimission capabilities, and the size and weight of the optimum engine cycle. Its capabilities are demonstrated over three combat mission applications. The results are presented to indicate the optimum designs over these missions, interaction effects of a few design variables, and the future course of developments in propulsion-system technology. The results also include a preliminary estimate of the impact of thrust-vectored takeoff and landing and a variable-capacity, low-pressure turbine on engine-cycle selection and overall aircraft sizing.

Nomenclature

T_{AB} = afterburner exit temperature
W_{EMP} = empty weight
$W_{ENG,DP}$ = engine-design point mass flow
$W_{F,msn}$ = fuel consumed over design mission
W_{TO} = aircraft takeoff gross weight

Introduction

THE propulsion or engine unit when integrated with an airframe defines the aircraft weapon system. The design and development of an aircraft weapon system must aim at successfully meeting the primary role that is defined by a set of military requirements based on perceived threats, present and/or futuristic. The propulsion unit has a long developmental period, a high cost of development, and it plays a dominant role in aircraft weapon-system performance, thereby making conceptual design decisions very critical.

Thus, when a new weapon system design is initiated it is extremely important to identify an optimum engine cycle in the conceptual-design phase. This optimum engine cycle must be one where the weapon system would be most responsive, in terms of performance as well as cost, to the requirements of a baseline design mission. The performance of the resulting weapon system on alternate missions, i.e., on off-design missions, is required to assess its multimission capabilities, which largely determines the affordability.

Because the present study is configured around the propulsion system a logical extension is to translate the optimum cycle into a preliminary envelope and estimate its weight. The sensitivity studies are important during conceptual design as they determine the trends and tradeoff involved in propulsion-system development. The variable-cycle engines and in-flight thrust vectoring are current indicators of next-generation propulsion systems. It would be worthwhile to explore the payoff of such capabilities and their impact on engine-cycle selection.

An explicit analytical model of the problem is not possible because of the complicated logic flow. A conceptual-design software has therefore been developed because it permits the simulation of complicated logic flow without any simplification. This paper presents the solution methodology and several case studies to demonstrate the capabilities of the software as applied to the art of conceptual design. Its content is based on the work reported in Sanghi.[1]

Solution Methodology

Optimum Engine-Cycle Identification

A propulsion concept is defined by a set of engine-design variables. Assigning numerical values to each of the variables creates an engine-design option within the selected propulsion concept. The design mission analysis, i.e., evaluation of an engine-design option over the specified mission, must account for its interactions with the airframe. The airframe, like the engine, is also defined by a set of airframe-design variables.

In design-mission analysis,[1] $W_{ENG,DP}$ and W_{TO} are determined such that the installed thrust demand of the most constraining segment is met and the weapon system consumes all of the fuel except the reserves while flying the mission. The outcome of design-mission analysis is the system response; its computer simulation is termed design simulator. The supercruise, i.e., supersonic cruise or low-altitude/high-subsonic cruise, in engine dry mode is usually the most constraining segment to size $W_{ENG,DP}$. Alternately, takeoff and/or sustained-turn performance may also be used to size $W_{ENG,DP}$.

A nonlinear constrained optimization problem is formulated to locate the optimum design set, which is an n dimensional vector of design variables being optimized, i.e., $\boldsymbol{X} = (x_1, x_2, \ldots, x_n)$. The minimization of W_{TO} is used as the figure of merit because a smaller weapon system costs less to build and operate. The "optimization with surface fits approximations"[2] has been used. The response, instead of being called directly from the design simulator, is made available to an optimization algorithm as surface fits. The surface fits are generated by doing parametric studies within the chosen design space, together with regression analysis on resulting data. The design of ex-

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periments techniques are used to perform multidimensional parametric studies efficiently and economically.

Off-Design Mission Analysis

Off-design mission analysis permits preliminary evaluation of the multimission capabilities of an optimum design. All of the weapon-system parameters, engine as well as aircraft, are completely defined. The choice of external payload such as bombs, missiles, external fuel tanks, etc., determines the weapon-system configuration, fuel capacity, and its W_{TO}.

The $W_{ENG,DP}$ and a prespecified power setting controls the installed thrust and corresponding specific fuel consumption (SFC) over the entire flight envelope. The performances during takeoff, acceleration, climb, sustained turn, and landing are evaluated as responses. The range of one or more cruise segments is evaluated from the fuel capacity.

Engine Sizing and Weight Estimation

The engine-sizing and weight-estimation methods are founded on the basis of past and current experience and give a preliminary set of results that are consistent with conceptual design accuracy. The mathematical basis of engine sizing to construct a gas flow path (GFP) layout is described in Shlyakhtenko[3] and Pera et al.,[4] whereas weight estimation is taken from Ref. 4. Reference 5 is the English translation of engine-sizing aspects that are discussed in Ref. 3 (in Russian). Reference 1 gives a complete overview of engine sizing and weight estimation based on the contents of Refs. 4 and 5. It also describes the design database and a constraint system to ensure the aerothermomechanical compatibility of an engine GFP layout.

Thrust-Vectored Takeoff/Landing

The ability to operate from short/damaged runways makes short takeoff and landing runs a major design criteria for future combat missions. It tends to drive the optimum to a low-wing-loading configuration. Such a design may not optimally meet the performance of remaining mission segments, in particular supercruise, and will result in a penalty in $W_{ENG,DP}$ and W_{TO}. Thus, to have a balance between short takeoff and landing and remaining mission segments, thrust vectoring during takeoff and landing may be highly beneficial.

The installed thrust line is assumed to be vectored by tilting the engine nozzle at a prespecified angle during takeoff and landing. The prespecified thrust-vectoring angle (TVA) is used as fixed design data. The optimum design set(s) will be valid only for the chosen values of TVA during takeoff and landing.

Variable-Cycle Engines

The variable-area turbine is an attractive option because it enables in-flight variation of bypass ratio (BPR), thereby improving the adaptability of engine to aircraft requirements. A large number of other variable-cycle concepts have been proposed and are under different levels of research/development, but a study of each of them is beyond the scope of the present work. The basis of the present study is purely conceptual and mechanical feasibility criteria is ignored. In view of the hostile environment of the high-pressure (HP) turbine, variable area is incorporated only in the low-pressure (LP) turbine. The area variation of LP turbine as a function of Mach number is prespecified. Because the area variation is a functional relation, it cannot be used as a design-set variable. Hence, it forms fixed design data and optimum and is valid for specified area variation.

Design-Set Variables

A large number of design variables participate in multidisciplinary conceptual design. Using each of them will increase the problem size and associated volume of data. Thus, only important design variables are included in a design set for parametric studies. The remaining are kept fixed at a preassigned numerical value, consistent with the projected level of technology.

As per current trends the twin-spool-mixed-flow-turbofan and twin-spool-turbojet types of propulsion concepts are investigated. The sea-level static condition in international standard atmosphere is taken as the engine-design point, which is the reference point for the numerical specification of engine-cycle parameters. For a mixed-flow turbofan, cycle parameters used in the design set are BPR, overall pressure ratio (OPR), maximum turbine entry temperature (TET) (TET_{max}), throttle ratio (TR), and maximum T_{AB} ($T_{AB,max}$). The TR is the ratio of TET_{max} to its design-point value (TR = TET_{max}/TET_{DP}), which defines the numerical value of TET_{DP}. For a twin-spool turbojet, instead of BPR, the pressure ratio of LP compressor is used.

On the airframe side, variation of lift, zero lift, and induced-drag coefficients with Mach number that are typical of a modern combat aircraft are assumed. The W_{EMP} is estimated as a function of W_{TO}, based on statistical correlations derived from past experience.[6] The internal fuel capacity is taken as $W_{F,msn}$. It eliminates design variables such as aspect ratio, wing sweep, thickness ratio, taper ratio, etc., from the design set. It is consistent with the problem definition because emphasis is more on the propulsion side, and the design phase addressed to is the conceptual design.

The W_{EMP}[6] is for conventional metallic construction. A correction factor is used to account for the reduction (because of the use of advanced materials) in estimated W_{EMP}. It enables one to investigate the impact of varying levels of aircraft construction technology on engine-cycle selection. To facilitate the computation of mission-matched $W_{ENG,DP}$, wing loading (WLDG) is chosen as an independent variable, and thrust loading (TLDG) is obtained as a response.

A few of the mission specifications out of the range, endurance, and performance levels may also be included in the design set to investigate their influence on the optimum design. The important response variables are W_{TO}, W_{EMP}, $W_{F,msn}$, wing area, TLDG, $W_{ENG,DP}$, and the performance of segments such as takeoff, constant altitude acceleration, climb, sustained turn, and landing.

Software Development

The design simulator is the critical component of conceptual-design software for optimum engine-cycle selection. It requires the integration of engine performance (installed thrust and SFC), airframe-design data, mission application, and weapon system equations of motion. Reference 1 gives the complete description of information flow logic in the design simulator.

The engine-component maps are not available during conceptual-design studies, and alternate methods that work without component maps have been used.[7,8] Reference 1 illustrates the specific tailoring of these methods for integration into the design simulator and the estimation of installation penalty. Mathematical descriptions of aircraft equations of motion and its weight, lift, drag, and drag-rise characteristics that are typical of modern combat aircraft are in Refs. 1, 6, and 8.

The description of Refs. 9 and 10 has been utilized to develop the computer simulation of stepwise regression analysis and the selection of design combinations (within a prespecified design space), where response is computed during surface-fit development. The "complex method of box"[11] has been used to identify the optimum. It does not require derivatives of the objective and constraint functions because it is computationally simple and easy to program.

References 3–5 are used to evolve the digital simulation of engine sizing and weight estimation. With suitable modifications in design simulator the off design simulator can easily be developed; it completes the development of conceptual-design software.

Validation

The design simulator has been validated with respect to an air-combat mission analysis case study.[8] For the same values of cycle parameters, W_{TO} and WLDG as given in Ref. 8, the computed $W_{F,msn}$ and $W_{ENG,DP}$ are within $\pm 2\%$ of their reference values.[8] The engine model has also been independently validated with respect to a baseline reference that makes use of component characteristics. The thrust and SFC at the maximum and three-part power settings, in the dry as well as reheat mode, compare within a maximum of $\pm 5\%$ over a wide range of altitudes and Mach number conditions. The detailed validation results for the engine model and design simulator are in Ref. 1.

The computer simulation of the regression analysis, design selection, and optimization algorithms has been validated against a large number of test cases from the open literature. The results are reproduced very closely, thereby justifying adequate confidence in their use in the present study.

An attempt was made to reproduce an existing weapon-system configuration[1] to validate the software in integrated form. The optimum identified by it is given next, which approximates the actual design fairly well: BPR = 0.20, OPR = 21.86, TET_{max} = 1700 K, TR = 1.1323, $T_{AB,max}$ = 2100 K, WLDG = 258.1 kg/m^2, $W_{F,msn}$ = 4198 kg, $W_{ENG,DP}$ = 74.7 kg/s, W_{TO} = 9680 kg, and TLDG = 0.80.

The validation case studies, illustrating the accuracy of off-design mission analysis, engine sizing, and weight estimation are contained in Ref. 1. The validation of every constituting block as well as the validation in integrated form attaches sufficient justification to the use and reliability of conceptual-design software.

Results

Optimization Studies

Optimization studies over three design missions[1] have been performed, i.e., high altitude air-combat mission, low-altitude air-defense mission, and high-altitude intercept mission. These missions include short takeoff and landing; loiter; mix of subsonic, transonic, and supersonic legs; high maneuverability; persistence; and supersonic dry cruise. The impact of increased supersonic requirements in air-combat mission, referred to as modified air-combat mission, has been investigated.

A total of six design-set variables are chosen. Their description, together with design space is as follows:

$0.10 \le$ BPR ≤ 1.0
$20.0 \le$ OPR ≤ 30
1700 K $\le TET_{max} \le$ 2000 K
$1.00 \le$ TR ≤ 1.20
1800 K $\le T_{AB,max} \le$ 2100 K
250 kg/m^2 $\le$ WLDG $\le$ 500 kg/m^2

The TET_{max} gets pushed to its upper limit (2000 K) during optimization. It therefore was kept fixed at 1900 K during optimization, consistent with near-term (year 2000) technology level.

(I) High-Altitude Air-Combat Mission (Twin-Engine Configuration)

The formulation of the optimization problem is as given next where BCA and BCM are best cruise altitude and best cruise Mach number, respectively.

Minimize W_{TO}, subject to:
(I) box constraints, i.e., design space and
(II) and inequality constraints ($g_1 \ldots . g_8$):
(g_1) Thrust loading ≤ 1.30
(g_2) $W_{ENG,DP} \le 200$ kg/s
(g_3) Takeoff ground run (S_{TO}) ≤ 450 m
(g_4) Load factor in sustained turn at $H = 9.0$ km, $M = 1.6 \ge 5.0$
(g_5) Load factor in sustained turn at $H = 9.0$ km, $M = 0.9 \ge 5.0$
(g_6) Acceleration time at $H = 9.0$ km, $M = 0.80$–$1.50 \le 50.0$ s
(g_7) Landing ground run (S_{LND}) ≤ 450 m
(g_8) Time to climb to BCA/BCM from sea level ≤ 150 s

The constraint g_2 ensures that the resulting fighter can at most be a twin-engine aircraft where $W_{ENG,DP}$ per engine is not allowed to exceed 100.0 kg/s, although it is desirable to keep it within 70.0–80.0 kg/s, as per existing design practices. The supercruise at 9.0 km and a Mach number of 1.50 is used to size $W_{ENG,DP}$. In Table 1, ENGINE-A is the baseline optimum for the W_{EMP} reduction of 15% as compared to conventional metallic construction. ENGINE-B is the optimum for further improvements in construction technology, i.e., the W_{EMP} reduction of 25%. As weapon systems become lighter, the use of a higher TLDG further reduces W_{TO}, i.e., ENGINE-C. The SI system of units has been used, except for weight, which is in kilograms.

(II) Low-Altitude Air-Defense Mission (Single-Engine Configuration)

Minimize W_{TO}, subject to:
(I) Box constraints, i.e., design space and
(II) and inequality constraints ($g_1 \ldots . g_8$):
(g_1) Thrust loading ≤ 1.00
(g_2) $W_{ENG,DP} \le 100$ kg/s
(g_3) $S_{TO} \le 500.0$ m
(g_4) Load factor in sustained turn at $H = 3.0$ km, $M = 0.90 \ge 6.5$
(g_5) Load factor in sustained turn at $H = 3.0$ km, $M = 0.85 \ge 6.5$
(g_6) Acceleration time at $H = 3.0$ km, $M = 0.77$–$0.90 \le 60.0$ s
(g_7) $S_{LND} \le 450.0$ m
(g_8) Time to climb to BCA/BCM from sea level ≤ 150 s

The supercruise at 3.0 km and Mach number of 0.90 is used to size $W_{ENG,DP}$. The ENGINE-D is the optimum for a weight reduction of 25% with respect to conventional metallic construction: BPR = 0.80, OPR = 30.00, TET_{max} = 1900 K, TR = 1.0970, $T_{AB,max}$ = 1800 K, WLDG = 304.10, fan pressure ratio (FPR) = 3.388, $W_{ENG,DP}$ = 79.30, W_{TO} = 8806.0, and TLDG = 0.81.

(III) High-Altitude Supersonic Intercept Mission (Twin-Engine Configuration)

Minimize W_{TO}, subject to:
(I) Box constraints, i.e., design space and
(II) and inequality constraints ($g_1 \ldots . g_7$):
(g_1) Thrust loading ≤ 1.2–1.5
(g_2) $W_{ENG,DP} \le 200$ kg/s

Table 1 Optimum over air-combat mission

Variables	A	B	C
BPR	0.61	0.80	0.7490
OPR	26.0	27.8	29.43
TET_{max}	1900 K	1900 K	1900 K
TR	1.138	1.168	1.0971
$T_{AB,max}$	1935 K	1800 K	1800 K
WLDG	358.6	370.0	400.0
FPR	3.448	3.014	3.4633
$W_{ENG,DP}$	72.5	57.5	57.5
W_{TO}	10,474	7693	7498
TLDG	1.30	1.28	1.39

(g_3) $S_{TO} \leq 450.0$ m
(g_4) Time to climb to BCA/BCM from sea level ≤ 120 s
(g_5) Acceleration time at $H = 10.5$ km, $M = 0.87–1.60 \leq 60.0$ s
(g_6) Load factor in sustained turn at $H = 10.5$ km, $M = 1.6 \geq 5.0$
(g_7) $S_{LND} \leq 450.0$ m

The supercruise at 10.5 km and at a Mach number of 1.6 sizes $W_{ENG,DP}$. In Table 2, ENGINE-E and ENGINE-F are the optimum for the W_{EMP} reduction of 15 and 25%, respectively, with respect to conventional metallic construction. The comparison of $W_{ENG,DP}$ and W_{TO} indicates that the use of advanced construction technology is highly desirable.

(IV) Modified Air-Combat Mission (Twin-Engine Configuration)

The optimization problem is the same as that for high-altitude air-combat mission, except that supersonic turn is performed at a Mach number of 1.80 and supercruise at 9.0 km and a Mach number of 1.8 sizes $W_{ENG,DP}$. In Table 3 ENGINE-G is the baseline solution at a W_{EMP} reduction of 15%. Here, the BPR has decreased while TR has increased with respect to design A. This is as expected because of the increased thrust demand during supercruise and at supersonic turn because of higher levels of Mach number. ENGINE-H is the optimum for advanced construction technology, i.e., a W_{EMP} reduction of 25%. At a W_{EMP} reduction of 25%, additional savings of 1.25% in W_{TO} result by increasing TLDG, as shown in optimum at ENGINE-I.

The foregoing case studies adequately reveal the capability of the software to identify optimum engine cycles. To optimally meet the postulated combat-mission roles, results indicate the need for new engine cycles(s) with enhanced capabilities.

The increasing level of TET_{max} and thereby a more powerful core shows trends toward increased BPR, increased OPR, and reduced $T_{AB,max}$. The increased BPR and OPR improve SFC, provide savings in mission-fuel usage and W_{TO}, and lower $T_{AB,max}$ reduces the observable [observable refers to aircraft being observed (as detected) because of high temperature in engine exhaust]. The higher levels of TET_{max} also aid in keeping $W_{ENG,DP}$ per engine within acceptable limits of 70–80 kg/s. Because of the reduced core size at higher BPR and OPR, the use of a moderate fan-pressure ratio is indicated to prevent an increase in aerodynamic loading on fan and/or fan–turbine. The TR is typically in the range of 1.10–1.20. Its exact value is dictated by the compromise between the degree of supersonic requirements, a balanced thrust lapse over the entire flight regime, and an acceptable level of fan-pressure ratio. The WLDG is driven to the highest value in feasible domain to reduce the thrust demand at supercruise. Its increase is constrained by short takeoff and landing and subsonic maneuvers.

The improved engine cycles together with advancements in weapon-system construction technology have a synergistic effect. For every kilogram of saving in W_{EMP}, the savings in W_{TO} are of the order of 1.50 kg.

At a given level of construction technology, TLDG ≤ 1.30 has been used to identify the baseline optimum engine cycle for twin-engine aircraft. The use of higher TLDG provides savings in W_{TO}, but it is permissible provided that 1) $W_{ENG,DP}$ is consistent with existing design trends, ≤80 kg/s/engine; and 2) high-component loading in fan and fan–turbine is possible to achieve higher fan pressure ratio at high BPR, without penalty of an additional fan or fan–turbine stage.

On similar lines, TLDG is constrained to 0.80 for single-engine aircraft.

Sensitivity Studies

The preceding optimization studies also illustrate sensitivity with respect to advanced construction technology, increased TLDG, and supersonic Mach number. As another illustration, sensitivity studies are performed to determine the tradeoff between BPR and $W_{ENG,DP}$, at a TET_{max} of 2000 K. The upper limit of BPR is increased to 1.0 in its design space. The BPR is held fixed at a preassigned numerical value and remaining design-set variables are reoptimized. The results are given in Table 4 for a range of BPR over the high-altitude air-combat mission.

The optimum BPR at the initial baseline solution is 1.0, which is on higher side. The high BPR reduces specific thrust, results in an increase in $W_{ENG,DP}$ and, hence, a higher engine frontal diameter. The engine integration with airframe may increase overall drag in such cases and reduction in BPR is warranted to offset the increase in $W_{ENG,DP}$. It, of course, will be at the cost of reduced savings in fuel consumption and a higher W_{TO}. From Table 4 it can be seen that $W_{ENG,DP}$ decreases with a decrease in BPR. The optimum at BPR of 0.60 is chosen as the final design. Upon comparison with baseline optimum, $W_{ENG,DP}$ decreases by 13 kg/s at the cost of increased W_{TO} by 220.0 kg.

The load factor in sustained turn at 9.0 km and a Mach number of 0.90 is the active constraint, its value being 5.0. It is relaxed to 4.80 and a new optimum is located. The $W_{ENG,DP}$ reduces by 20.0 kg/s, without any penalty in W_{TO}, with respect to baseline optimum. A twin-engine aircraft with a $W_{ENG,DP}$ of 78.0 kg/s is fairly acceptable. It therefore may be worthwhile to consider a slight relaxation of sustained turn constraint to 4.80. The preceding study also illustrates the ease with which sensitivity studies are performed to determine the tradeoff in engine-cycle selection.

Engine thrust/weight T/W ratio is the technology parameter that represents the net effect of advancements in aerodynamics, thermodynamic cycle, materials, and construction technology.

Table 2 Optimum solutions over air-intercept mission

Variables	E	F
BPR	0.4946	0.5247
OPR	28.18	29.3243
TET_{max}	1900 K	1900 K
TR	1.1124	1.0901
$T_{AB,max}$	1800 K	1800 K
WLDG	377.30	393.70
FPR	3.80	3.8823
$W_{ENG,DP}$	100.6	75.1
W_{TO}	15,590	10,987
TLDG	1.21	1.30

Table 3 Optimum solutions over modified air-combat mission

Variables	G	H	I
BPR	0.3425	0.7912	0.786
OPR	26.52	26.97	27.55
TET_{max}	1900 K	1900 K	1900 K
TR	1.1885	1.1924	1.1601
$T_{AB,max}$	1962 K	1800 K	1800 K
WLDG	392.20	416.50	434.45
FPR	3.5953	2.9153	3.0758
$W_{ENG,DP}$	80.50	71.5	74.0
W_{TO}	12,037	8421	8316
TLDG	1.30	1.42	1.52

Table 4 Tradeoff: BPR vs $W_{ENG,DP}$

BPR	WLDG	W_{TO}	$W_{ENG,DP}$
1.00	353.98	11,522	175.50
0.90	351.90	11,525	170.50
0.80	350.11	11,577	167.60
0.70	348.67	11,642	164.84
0.60	347.94	11,741	162.50

The assessment of payoff caused by the increase in engine T/W ratio has been made by studying its overall impact on aircraft weapon systems.

The baseline engine T/W ratio, which represents the current level of technology, has been taken as 8.5. Thus, the impact of its increase, first to 10 and then to 12, on the weapon system has been estimated. Two mission applications are chosen: 1) the intercept mission, with optimum at F as the baseline reference, and 2) the air-combat mission, with optimum at A as baseline reference.

The W_{EMP} from statistical correlations[6] includes the airframe and engine weight. With a baseline engine T/W ratio of 8.5 and knowing sea-level static thrust as computed during cycle optimization, the engine weight is computed. It provides an explicit estimate of airframe weight. At a constant airframe weight the engine T/W ratio is increased to 10. It reduces engine weight and, hence, W_{EMP}. Using the baseline optimum design the design simulator is run for reduced W_{EMP} that corresponds to a T/W ratio of 10.

Because of reduced W_{EMP}, the W_{TO} also reduces. At constant WLDG it reduces the wing area and, hence, the overall aircraft drag. Thus, $W_{F,msn}$ and engine-thrust requirements also reduce, leading to a smaller engine. The decrease in sea-level static thrust at a constant-engine T/W ratio causes further reduction in engine weight and, therefore, in W_{EMP}. The design simulator is run again for reduced W_{EMP}. The process continues until two successive values of engine weight match within $\pm 0.10\%$. The results of such a study are presented in Tables 5 and 6, when the engine T/W is increased to 10.0.

When the engine T/W ratio is increased to 12.0, savings in $W_{ENG,DP}$ and W_{TO} increase to 6.85 and 8.10% over the intercept mission, and to 6.95 and 7.65% over the air-combat mission. Thus, having designed the engine for a certain baseline T/W ratio, derivative engines must be attempted with increased T/W ratio. It not only results in a lighter weapon system but also reduces the engine size.

To perform sensitivity studies with respect to design-set variables, one design-set variable is chosen at a time. It is held fixed at a preassigned numerical value and remaining design-set variables are reoptimized. The resulting percent change in W_{TO} as a result of change in the numerical value of chosen design-set variables is shown in Fig. 1 for TET_{max} and TR.

The results show that increasing TET_{max} is always beneficial, whereas TR will have the optimum somewhere in between its design limits, indicating that it is a compromise between various mission requirements.

Table 5 Impact of engine T/W ratio over intercept mission

Variables	Engine $T/W = 8.5$	Engine $T/W = 10.0$	% saving
W_{ENG}	1,672.0	1,375.0	17.75
$W_{ENG,DP}$	150.30	145.40	3.25
$W_{F,msn}$	4,394.0	4,230.0	3.75
W_{EMP}	5,186.0	4,889.0	5.70
W_{TO}	10,986.0	10,525.0	4.20

Table 6 Impact of engine T/W ratio over air combat mission

Variables	Engine $T/W = 8.5$	Engine $T/W = 10.0$	% saving
W_{ENG}	1,598.0	1,305.0	18.30
$W_{ENG,DP}$	143.80	138.10	3.95
$W_{F,msn}$	3,425.0	3,282.0	4.15
W_{EMP}	5,643.0	5,350.0	5.20
W_{TO}	10,474.0	10,038.0	4.15

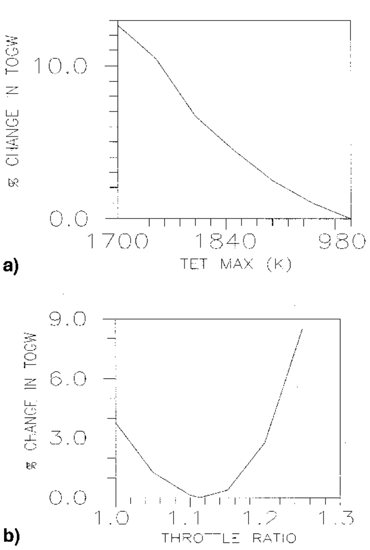

Fig. 1 Sensitivity studies with respect to a) TET_{max} and b) throttle ratio.

Use of Alternate Options

Besides supercruise, takeoff and maneuver segments were used as added constraining segments to size $W_{ENG,DP}$. It did not significantly alter the location of the optimum. Thus, if present, the use of supercruise as the only constraining segment is sufficient. Similarly, the use of a constant component efficiency and constant specific heat in engine-performance estimates were observed to be sufficient during optimization studies.

Off-Design Mission Analysis

The preceding configurations are for air combat and intercept missions. As an example of off-design mission analysis, the optimum design A, stated earlier, is evaluated over close air-support mission. The $W_{ENG,DP}$, W_{EMP}, wing area, and internal fuel capacity are fixed. The range of cruise segments 3 and 17, i.e., X_3 and X_{17}, is determined based on fuel available. The results are presented in Table 7 for external fuel values, i.e., I, no external fuel; II, one 120-gal fuel tank on the centerline pylon; and III, one 300-gal fuel tank on the centerline pylon.

The off-design simulator results indicate the adequacy of weapon system A for a close air-support mission. Having frozen the initial design, one or more of the design variables may deviate from their baseline value, e.g., variations in engine and/or airframe weight, not being able to achieve the optimum engine cycle in actual hardware, variations in design-point efficiency of engine components, etc. The off-design simulator can easily ascertain the impact of such variations on weapon system response.

Turbofan vs Turbojet

In accordance with existing military trends earlier case studies were configured around mixed-flow turbofan. The optimum engine cycle and corresponding weapon system configuration

Table 7 Off-design mission analysis over close air-support mission

Configuration	W_{TO}	External fuel	S_{TO}
I	13,099	0.0	569.0
II	13,549	350.0	597.0
III	14,124	875.0	634.0
	Load factor/C_L	S_{LND}	X_3/X_{17}
I	7.35/0.60	405.0	60.0
II	7.19/0.59	407.0	118.0
III	7.04/0.59	407.0	206.0

is now identified for the turbojet engine concept. The baseline reference is weapon system B. The BPR is 0.0 for turbojet. The TET_{max} and T_{AB} are kept fixed at 1900 and 1800 K, respectively, from the experience of baseline reference. Thus, only three design-set variables were used for parametric variation:

$$18.0 \leq \mathrm{OPR} \leq 30.0$$
$$1.0 \leq \mathrm{TR} \leq 1.20$$
$$325 \leq \mathrm{WLDG} \leq 450$$

Keeping the constraint system the same as in the baseline reference, the optimum was derived. Upon comparison with the baseline reference, it was observed that $W_{ENG,DP}$ decreases by 14.70%, but at the cost of a 14.60% increase in W_{TO}. It indicates that mixed-flow turbofan is a more suitable choice, thereby justifying its use in earlier optimization studies.

Engine Sizing and Weight Estimation

Engine A is chosen to show the application of engine sizing and weight estimation. Its length L, weight and frontal diameter D for two different compressor configurations are given in Table 8. The HP and LP turbines are each single stage. Z is the number of stages, and rpm is revolutions per minute. Subscript Fan is for a fan/LP compressor, and HPC is for an HP compressor.

Consistent with design trends of Ref. 1, the second configuration uses an advanced level of technology. It causes a weight and length reduction of 6 and 8%, respectively. Its GFP is shown in Fig. 2.

Thrust-Vectored Takeoff/Landing

The optimization studies stated in Table 9 have been performed over an intercept mission to investigate the payoffs of thrust vectoring and its influence on the optimum. The S_{TO} and S_{LND} are constrained to 350 m instead of 450 m. The supercruise at 10.5 km and Mach number of 1.8 is used to size $W_{ENG,DP}$. The weight reduction of 25% is used with respect to conventional metallic construction. The resulting W_{EMP} is increased by 4% to account for incorporating thrust vectoring.[6]

In optimum without thrust vectoring at J, short takeoff and landing force a low WLDG; thereby resulting in a twin-engine configuration where the $W_{ENG,DP}$ of each engine is 102.1 kg/s. It violates the existing design trends. Thus, the TVA of 30 deg is used during takeoff and landing, leading to optimum design K. It permits the use of higher WLDG, causing large reductions in W_{TO} and $W_{ENG,DP}$, with respect to case J.

The S_{LND} is an active constraint in case-study K. Thus, TVA during landing only has been increased to 45 deg, resulting in optimum design at L. It permits landing at a still higher WLDG, causing an increased reduction in W_{TO} and $W_{ENG,DP}$. The liftoff and touchdown speeds decrease by 30 and 12.50%, respectively, compared to a situation if the optimum as shown in the preceding text did not have thrust vectoring. W_{TO} and $W_{ENG,DP}$ with respect to case-study J decrease by 20 and 24%, respectively.

Table 8 Engine sizing studies

	L, m	W_{ENG} kg	D, m	Z_{Fan}/rpm	Z_{HPC}/rpm
1	3.8	783	0.707	4/11,007	9/17,145
2	3.5	735	0.707	3/12,029	7/16,717

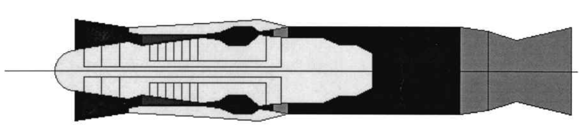

Fig. 2 Engine GFP layout. Frontal diameter, 0.7066 m; engine length, 3.4686 m; and engine weight, 734.6 kg.

Table 9 Optimum solutions with thrust-vectored takeoff/landing

Variables	J	K	L
BPR	0.20	0.3437	0.5541
OPR	22.37	24.655	26.30
TET_{max}	1900 K	1900 K	1900 K
TR	1.1076	1.18	1.1494
$T_{AB,max}$	1800 K	1800 K	1800 K
WLDG	285.0	349.0	390.3
FPR	4.4658	3.6636	3.4665
$W_{ENG,DP}$	204.20	153.8	155.3
W_{TO}	15,578	13,455	12,407
TLDG	1.2962	1.0574	1.1336

Hence, use of thrust vectoring during takeoff and landing is very beneficial. During landing aircraft use only as much engine power that is needed to balance the drag and maintain forward speed. To augment the lift component of vectored thrust and to have landing at higher WLDG, higher TVA is needed during landing. It also makes the engine cycle move to a higher BPR and OPR, leading to increased savings in W_{TO}.

Because of the lack of exact mission definition and supporting modeling information, discussion on thrust vectoring has been restricted to takeoff and landing only. It is justifiable during conceptual design because it is the constraining limits of S_{TO} and S_{LND} that largely influence the definition of optimum. The other payoffs can then be obtained as responses.

Variable-Area Low-Pressure Turbine

The optimum engine cycle, with a variable area LP turbine was identified over the air-combat mission. A high value of 1.20 was chosen as the design BPR and the TET_{max} was kept fixed at 1900 K. The LP turbine throat area was opened up to 15% at supersonic Mach numbers to reduce the net-operating BPR. When compared with the optimum response of a corresponding fixed-cycle engine, savings in $W_{F,msn}$ were 4 and 1%, respectively, for W_{EMP} reductions of 15 and 25% with respect to conventional metallic construction. The savings decrease with an increase in W_{EMP} reduction. This is because as the airframe becomes lighter, an optimum BPR of a fixed cycle engine increases from 0.65 to 0.80. It shows that as fixed cycle engines can be conceived for higher BPR, the payoffs because of variable cycle feature will reduce.

In another study variable-area LP turbine was used with an existing engine cycle, over a low-altitude air-defense mission. The W_{EMP} reduction of 15% with respect to conventional metallic construction was used. Because the engine cycle is of a low BPR type, the LP turbine throat was closed up to 15% at subsonic Mach numbers to increase the BPR. It results in a savings of 2.24% in mission fuel when compared with a fixed cycle engine. When the subsonic range was doubled the savings in mission fuel increased to 4.35%. As the W_{EMP} reduction increased to 25%, i.e., as aircraft becomes lighter, the savings reduce to 1.56 and 3.54%, respectively. It shows that for a given engine cycle, payoffs of a variable-area LP turbine depends on the type of mission application and the level of construction technology.

The benefits of a variable-area LP turbine engine diminish with a loss in efficiency because of area variation. The losses must be minimized to fully realize the potential payoffs of such a design concept.

Conclusions

The conceptual design software is a powerful aid to analyze a wide spectrum of design options in a reasonable time span, without gross simplification of the complex design process. It provides good visibility into the highly complex engine–airframe synthesis process and enables the designer to make a more rational decision free of personal biases and conventional design practices, with adequate justification to the initial design proposal.

The methodology of optimization with surface fits has been reascertained as a fast, efficient, and powerful approach to identify an optimum engine–aircraft match during conceptual design. The use of a simple algorithm, i.e., complex method of box, has been demonstrated as an efficient optimization technique.

The results indicate that mixed-flow turbofan is more suitable than the turbojet. With increasing $\mathrm{TET}_{\max}$, engine cycles should be configured for higher BPR and OPR. The TR in the range of 1.10–1.20 is desirable to provide good supersonic performance. Because core size reduces with an increase in BPR and OPR, moderate FPR is desirable to prevent an increase in aerodynamic loading on an LP turbine. The more powerful core as a result of higher $\mathrm{TET}_{\max}$ requires a low $T_{\mathrm{AB,max}}$, with the added advantage of reduced observable.

The optimum WLDG takes the highest value in a feasible domain, which is defined by the intersection of active constraints. For every kilogram of reduction in W_{EMP}, the W_{TO} reduces by about 1.50 kg. Thus, besides improvements in engine cycles, advancements in aircraft construction technology also has large-scale benefits. As W_{EMP} decreases and supersonic requirements become more stringent, designing a weapon system for higher TLDG (in the range of 1.30–1.40) will lead to further savings in W_{TO}.

Having designed the engine for a certain baseline T/W ratio, attempts must be made to improve it. It provides reduction in the aircraft as well as engine size. The payoffs of variable-capacity LP turbine are dependent upon the type of engine cycle, level of construction technology, nature of mission application, and loss in efficiency caused by area variation. The thrust-vectored takeoff and landing is highly beneficial to simultaneously meet the requirements of supercruise and short takeoff and landing ground run.

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