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Role of Figures of Merit in Design Optimization and Technology Assessment

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An economical preliminary design procedure is discussed which transforms the complex relationships of a sophisticated design synthesis performance analysis into simpler second-order expressions through a regression analysis. These relationships can then be used to determine constrained optimal designs for a wide variety of figures of merit. A design study of military and commercial cargo transports is described in which optimum designs for seven different figures of merit are determined. Differences from previous studies due to technology representation are discussed and off-design penalties, trade boundaries, and design sensitivities are developed.

Introduction

CONSIDERABLE attention is being paid in current studies to the appropriate choice of figure of merit in airplane configuration assessment. The effect of different figures of merit such as direct operating costs, which emphasizes speed, and acquisition costs, which emphasizes empty weight, on configuration parameters such as wing sweep and aspect ratio is dramatic. Emerging technology must, therefore, be adapted in different ways depending upon the identified application. Assessment of the relative payoffs of various opportunities in advanced technology is also affected, so that the areas recommended for emphasis may depend to a large extent upon the figures of merit used in the analysis.

The Advanced Airplane Branch of the Boeing Military Airplane Company and its predecessor the Boeing Military Airplane Development Organization have conducted many parametric studies as a part of military contracts[1-3] and company-funded IR&D work.[4-6] In several recent studies[2,5] attention has been focused on the effect that figures of merit have on the selection of an aircraft configuration. In order to explore this further, an aircraft design data base was constructed for commercial and military transport aircraft. Optimum configurations were chosen for each of seven figures of merit. The methods by which this was done are explained below and the resulting designs are compared and discussed.

Analysis Techniques

One of the traditional objectives of airplane preliminary design is to identify high payoffs and risks in emerging technology to help provide the basis for allocation of engineering development resources. The available tools for conducting preliminary design studies run the gamut from prepared cookbook charts to complex analysis programs. There is, obviously, a wide variation of preparation time, engineering cost, and accuracy of answers between methods at opposite ends of the methods spectrum. Often the quick turnaround, canned preliminary design synthesis is deficient in depicting subtle differences in design concept or in accurately measuring the influence of changing mission and operational requirements. On the other hand, the flow time and cost required to implement sophisticated analysis procedures and to study the influence of a large selection of design variables have also often been unacceptable.

The usual procedure has been to rely on experience and quick "back of the envelope" studies to get into the "ball park" and then conduct a series of two- or three-dimensional parametric studies to establish a refined conceptual design. With the advent of large-scale, multiprocessing computers new techniques have been developed that provide economical, multidimensional design optimizations that are a substantial improvement in both flow time and data tolerance.

The development objectives in preliminary design techniques, broadly stated, is to have flexibility of application, short flow time, and high credibility of data in a system that can provide immediate answers to questions relating airplane configuration, size, and cost to mission requirements. Further the technique should provide the capability to determine the combination of design parameters that will produce the best design for minimum gross weight, minimum acquisition cost, minimum life cycle cost, or any other figure of merit deemed appropriate. It should be able to identify an optimum design within a constrained design space bounded by dimensional limits and/or secondary performance requirements. These are all properties of the preliminary design technique used in this study. The steps in the development of constrained optimal design points and tradeoffs are illustrated in Fig. 1. The process combines the capability of the Program Compiler Version 2.1[7] for rapid assembly of special-purpose design synthesis/performance analysis programs with the capability of the ARES data management system[8] to develop and use simple second-order relationships between design parameter inputs and the performance/cost outputs for design selection.

The complete flow is carried out in a CDC Cyber 175 computer as a discontinuous process. Step 1 is the construction of a suitable design synthesis/performance analysis program through the program compiler system. This is achieved by defining the analysis steps desired, mission profiles, and data input/output through the use of problem-oriented language statements (POLS) to a monitor program which, in turn, exercises appropriate precompilers. Beyond this point, the technique assumes that the outputs of the design and evaluation model can be adequately represented

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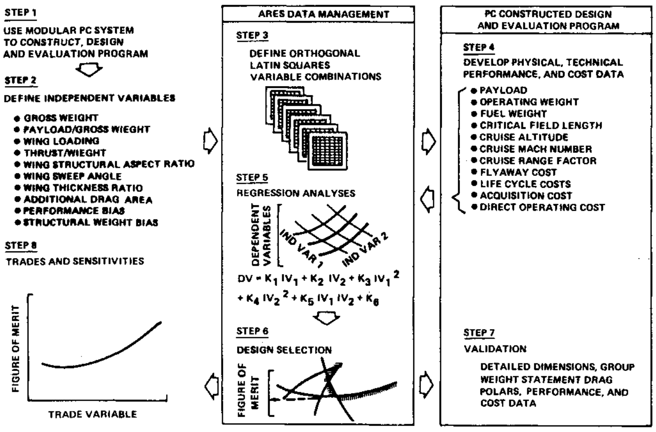

Fig. 1 Multidimensioned optimization approach.

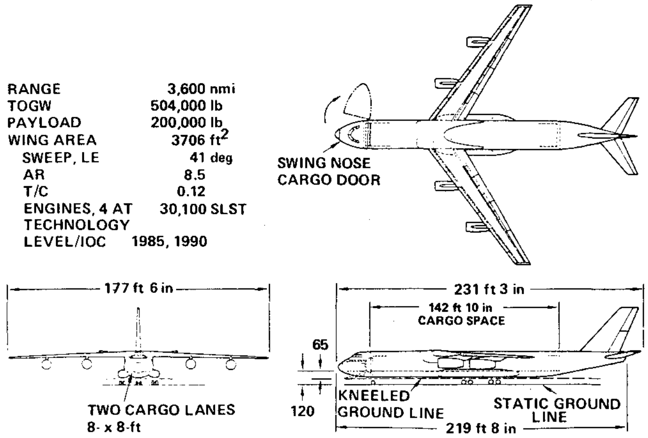

Fig. 2 Typical design concept.

over the region of interest with second-order expressions in the input variables (step 5). To derive these expressions, inputs to the model (step 4) are selected by the method of orthogonal latin squares in order to insure zero cross correlation in the regression analysis (step 3). The resultant second-order equations defining output variables can be exercised in a performance mode where all independent variables such as wing sweep, thickness, etc., are defined. Alternatively, a set of equations can be used to define a design that is optimum for some figure of merit (step 6). An interrogation can be performed under various physical or performance constraints. Before the results are considered valid and trade studies conducted (step 8), the design model can be used to confirm characteristics predicted by the polynomial representation (step 7).

This multivariable preliminary design approach has been used at Boeing on studies of a wide variety of aircraft including heavy transports,[1,2,5] long endurance patrol aircraft,[3] ship-based V/STOL aircraft,[4] as well as classified studies of combat aircraft. The data presented in this paper derive from continuing Boeing studies of the impact of advanced technology on heavy military and commercial cargo transports. The ground rules and technology projections, though unique to this study, are based upon experience in similar studies.

Airplane Design

Some of the typical design considerations for this type of aircraft that have impact on the formulation of the computer design model are: payload accommodation and loadability, mission range, field basing, operating environment, and technology availability. For instance, the military transport cargo box is determined from the design payload weight, the width and height of the largest dimensioned single piece of military cargo, and the average floor loading. On the other hand, the commercial cargo box is determined from the dimensions of the containerized payload. The high-wing configuration is generally preferred for military cargo aircraft because the low floor height provides ease of loading.

The scope of the study was limited to comparison of military and commercial cargo aircraft with the design requirements shown in Table 1. In order to match these requirements in the design selection process each configuration exercised for the data base was evaluated as both a military transport and a commercial transport. Even though there were differences in cargo handling and hence the operating weight of the two versions, the airframes were the same and were assumed to be built on a single production line.

Figure 2 shows the baseline design concept as a high-wing, four-engine cargo transport with a swing nose for loading. The fuselage-mounted main and nose gear can kneel to produce truck bed height loading. Control surface sizing was

Table 1 Typical design requirements

Military and commercial cargo versions of each configuration
Military version
Takeoff critical field length ≤8000 ft
Sea level, standard day, engine out climb gradient ≥0.03
Range mission
initial cruise altitude ≥28,000 ft
200,000 lb outsized payload
MIL-C-5011A ground rules
Commercial version
Takeoff FAR field length ≤10,000 ft
sea level, standard day
Provide cargo box cross section for two lanes, 8×8 ft
Gross payload to make same maximum zero fuel weight as military version

Table 2 Independent trade variables

Item	Range of variation
Takeoff gross weight, lb	300,000-800,000
Military payload/TOGW	0.15-0.45
Wing loading, lb/ft^2	90-170
Thrust/weight, FN_{SLS}/TOGW	0.17-0.27
Wing structural aspect ratio	7-15
Wing leading-edge sweep angle, deg	10-45
Wing mean thickness ratio	0.09-0.15

accomplished within the design synthesis program for typical stability and control criteria, such as engine-out trim.

The primary structure is bonded graphite epoxy. The propulsion is scaled advanced E3 technology turbofans and the wing aerodynamic technology is based upon use of supercritical sections. Structural load reduction is provided by an active control system. Cruise fuel flows have been reduced 10% as an additional technology gain for the time period of 1990 IOC. In this study the gain has been included as an additional reduction in specific fuel consumption, whereas in Refs. 1,2, and 5 similar projected technology gains were included as a reduction in cruise drag. Although the result is the same on cruise range factor, the drag reduction provides an additional gain in cruise ceiling not included in this study.

Computer-Aided Design Approach

The ARES data management system[8] provides for up to 10 independent variables in its regression procedures. For this study, however, only the seven listed in Table 2 were exercised. The range of variation in gross weight and payload ratio allows investigation of extremes in payload/range. Most of the boundary values of the variables are selected on the basis of past experience; however, some imply limits on the credibility of the design synthesis. Since the structural weights are based upon Class I statistical correlations augmented with simplified analytical procedures, the applicability to highly flexible, high-aspect-ratio, thin wings is limited. Even though load alleviation and modal suppression control systems are assessed to be in the technology available, a close prediction of wing weights depends on dynamic loads analyses outside the scope of the present effort.

A simplified flow diagram of the design synthesis program is shown on Fig. 3. This program, especially tailored for transport aircraft preliminary design studies, was constructed with the modular program compiler system.[7]

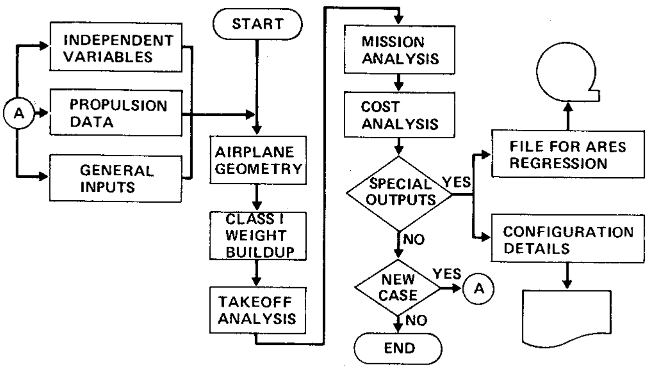

Fig. 3 Design synthesis/performance analysis.

Table 3 Typical program outputs

Total of 440 items in the output file are available for regression	
Physical characteristics:	
Fuselage length	Wetted areas
Wing span	Wing fuel volume
Tail arm lengths	Operating weight
Tail volume	Airframe unit weight
Tail areas	
Performance characteristics:	
Military critical field length	Military range
FAR field length	ATA range
Cruise Mach number	Cruise ceiling
Cruise altitude	
Cost Data:	
RDT&E cost	Fuel cost
Acquisition cost	Operating systems cost
Flyaway cost	Life cycle cost

In this system the user describes the program in POLS which are interpreted by a series of precompilers into the main program, the mission analysis, and the data transfer subroutines. Since only data supplied to the output data base may be used in the constraint and optimization procedure, the data output is usually very large and contains many items of remote concern to the immediate design question. Some of these items provide the basis for a series of continuing design studies from a single data base. Table 3 shows a partial list of outputs from the design synthesis computer model.

Table 4 lists results of the regression analysis for a number of the more significant outputs. The second-order equations representing each dependent variable may have up to 36 terms if all seven independent variables appear in all potential combinations. Some of the terms have a very weak influence, however, as noted by the difference between the total terms in the equation and the number of terms with influence coefficients greater than 0.1. Note that half the terms in the fuel equation are weak terms while none of the terms in the cruise Mach number equation are particularly weak. The last column in Table 4 shows a measure of the accuracy of the equation. This measure is the ratio, in percentage, of the standard deviation of residuals σR to the magnitude of the data interval Δ. These values range between a tolerance of less than 0.5% for fuel to about 5.5% for Mach number with the majority less than 1.2%.

Figures of Merit

The traditional design figure of merit in most preliminary design studies is gross weight. For this study comparisons have been made of designs optimized to the seven figures of merit: gross weight, life cycle cost (LCC), acquisition cost, flyaway cost, LCC/productivity, direct operating cost, and fuel.

Life cycle cost has been calculated for a 20 year life with a peacetime utilization of 1000 hours per airplane per year for a 200 airplane fleet in 1978 dollars. The acquisition cost is developed for a buy of 200 military airplanes from a common military-commercial development, and a total production run of 400 airplanes. Flyaway cost is the production cost per airplane, including spares. The ratio of life cycle cost to productivity is a measure of cost effectiveness. However, it is considered appropriate to measure peacetime costs and wartime productivity. Consequently the value is total life cycle dollars per ton-mile per 12 hour day of wartime use. Direct operating cost is computed for the commercial designs using the Airline Transport Association's standard international mission and 1978 cost formula.

Table 4 Regression analysis

			Data input delta		Terms in equation		
Variable	Multiple correlation coefficient squared	Standard deviation of residuals (σR)	From	To	Full	With influence coefficient ≥0.1	Tolerance of fit over the data interval $\sigma_R/\Delta\times 100$,%
Mission range	0.99900	88.28	1098	9270	28	26	1.08
Life cycle cost	0.99920	96.99×10^6	12×10^9	22.96×10^9	22	16	0.885
Acquisition cost	0.99915	78.27×10^6	6.957×10^9	15.290×10^9	23	18	0.939
Flyaway cost	0.99936	2.682×10^5	26.33×10^6	60.85×10^6	24	19	0.777
LCC/productivity	0.99619	4.1855	143.9	408.9	19	16	1.579
Direct operating cost	0.99542	0.001255	0.04672	0.1157	25	22	1.819
Fuel	0.99977	1486	41,850	381,600	26	13	0.437
TO distance	0.99964	49	3750	13,050	28	21	0.526
Second segment climb gradient	0.99181	0.000992	−0.02708	0.10470	23	19	0.753
FAR field length	0.99799	126	2876	13,260	22	21	1.216
Cruise altitude	0.99451	518	14,181	39,320	26	22	2.063
Cruise Mach number	0.96067	0.0166	0.5347	0.8389	12	12	5.458

Table 5 Selected designs

Item	Minimum gross weight	Minimum life cycle cost	Minimum acquisition cost	Minimum flyaway cost	Minimum LCC/ productivity	Minimum DOC	Minimum fuel
Gross weight, lb	504,000[a]	524,000	530,000	526,000	519,000	508,000	547,000
Wing loading, lb/ft^2	136	128	131	133	141	142	115
Thrust/weight	0.239	0.202	0.207	0.209	0.270[b]	0.238	0.191
Wing aspect ratio							
Structural	15[b]	10.2	11.0	9.8	8.5	13.2	15[b]
Aerodynamic	8.5	9.9	10.1	9.5	5.6	8.6	14.2
Wing leading-edge sweep, deg	41	10[b]	17	10	36	36	13
Wing mean thickness ratio	0.122	0.128	0.150[b]	0.137	0.090[b]	0.090[b]	0.090[b]
Life cycle cost, $B	17.7	16.6[a]	16.8	16.7	18.0	17.7	18.0
Acquisition cost, $B	11.4	10.7	10.7[a]	10.7	11.4	11.4	12.1
Flyaway cost, $M	43.5	40.9	40.9	40.8[a]	43.6	43.6	46.1
LCC/productivity, $/ton-mile-day	165	185	180	182	153[a]	162	200
Direct operating cost, $/ton-mile	0.0516	0.0567	0.0557	0.0563	0.0511	0.0497[a]	0.0567
Fuel, lb	115,000	127,000	133,000	133,000	138,000	119,000	111,000[a]
Takeoff distance, ft	8000[b]	8000[b]	8000[b]	8000[b]	7380	8000[b]	7680
Second segment ceiling climb gradient	0.0597	0.0454	0.0509	0.0444	0.0300[b]	0.0579	0.0643
Far-field length, ft	8230	8150	8030	8360	8770	8120	6490
Initial cruise altitude, ft	32,600	28,000[b]	28,000[b]	28,000[b]	29,800	32,500	31,200
Initial cruise Mach number	0.782	0.645	0.642	0.655	0.802	0.790	0.669
Wing area, ft^2	3706	4094	4046	3955	3681	3577	4757
Wing span, ft	177.5	201.3	202.1	193.8	143.6	175.4	259.9
SLS thrust per engine, lb	30,110	26,460	27,430	27,480	35,940	39,230	26,120

[a]Optimum design. [b]Boundary value.

Table 6 Design penalties

Off-design figure of merit	Penalty in off-design figure of merit, %						
	Gross weight	Life cycle cost	Acquisition cost	Flyaway cost	LCC/ productivity	DOC	Fuel
Gross weight	–	4.0	5.2	4.4	3.0	0.8	8.5
Life cycle cost	6.6	–	1.2	0.6	8.4	6.6	8.4
Acquisition cost	6.5	0	–	0	6.5	6.5	13.1
Flyaway cost	6.4	0.2	0.2	–	6.9	6.9	13.0
LCC/productivity	7.8	20.9	17.6	19.0	–	5.9	30.7
Direct operating cost	3.8	14.1	12.1	13.3	2.8	–	14.1
Fuel	3.6	14.4	19.8	19.8	24.3	7.2	–
Accumulative penalty	34.7	53.6	56.1	57.1	51.9	33.9	87.8
Average off-design penalty	5.78	8.93	9.35	9.52	8.65	5.65	14.63

Results

In Table 5 are listed the characteristics of airplanes matched to the design requirements of Table 1 and optimized to the seven figures of merit. Note that the minimum life cycle, acquisition, and flyaway cost designs are so similar that, within the tolerance quoted, their acquisition costs are identical. These three designs simultaneously match both the 8000 ft takeoff and 28,000 ft minimum cruise altitude requirements. On the other hand, the minimum gross weight and minimum direct operating cost designs are very similar. Both designs match the 8000 ft takeoff distance requirement with nearly the same thrust/weight ratio, but the higher sweep angle of the minimum gross weight design requires a lower wing loading. The similarity of these two, as might be expected, extends to their life cycle, acquisition, and flyaway costs. The two extremes in the group are the LCC/productivity and fuel optimized designs. The LCC/productivity airplane combines the highest wing loading, thrust/weight ratio, and span loading to get the highest cruise speed, while the minimum fuel airplane combines opposing characteristics of minimum wing loading, thrust/weight ratio, and span loading. These two designs, exceeding both takeoff and cruise altitude constraints, also have the extremes in climb gradient. Note that minimum fuel is gained at the expense of a large airframe with many accentuated design problems such as gust loads, taxi loads, and hangar accommodations. All of the cost figures of merit are at their peak values for the minimum fuel design.

The penalties associated with design to each figure of merit are shown on Table 6 as a percentage of the optimum value. The greatest penalties are mutually imposed by LCC/productivity and fuel on each other. The least penalties overall are imposed by gross weight or direct operating cost with an average of less than 6% to the off-design figures of merit. In any specific design study the relative importance of figures of merit may not be considered equal. In that case weighted figures of merit penalties could be developed.

Trade Studies

Investigations of compromises between one figure of merit and another show that the design surface is seldom flat. Since the design point minimum in any figure of merit represents the point of zero slope relative to that figure of merit, the boundary of potential designs between two minima is concave. An illustration of this boundary between the two figures of merit that are the extremes in configuration, LCC/productivity, and fuel, is shown on Fig. 4. This trade line represents a lower boundary on LCC/productivity at fuel values between the 111,000 lb of the minimum fuel optima and the 138,000 lb of the minimum LCC/productivity optima. Or conversely, it represents the lower bound of fuel between the LCC/productivity of 153 for the minimum

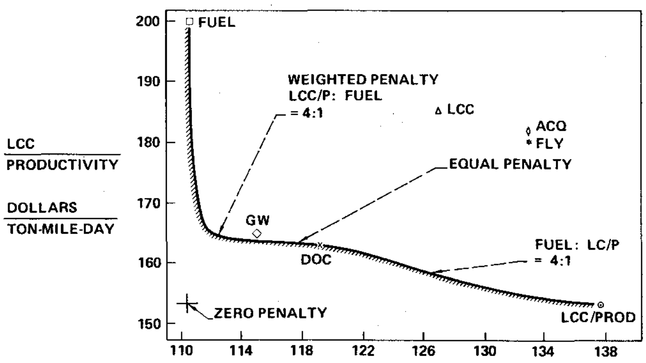

Fig. 4 Figure of merit trade boundary.

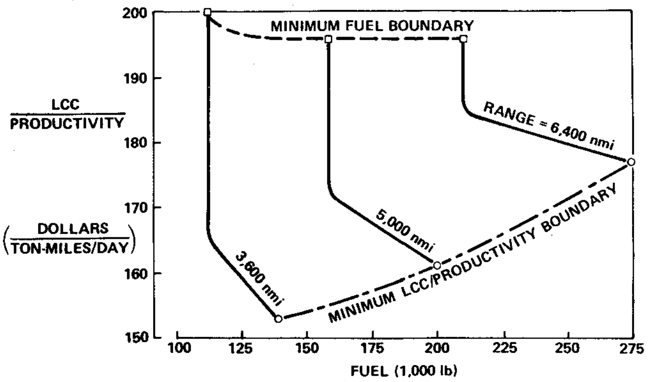

Fig. 7 Design requirement trade boundary.

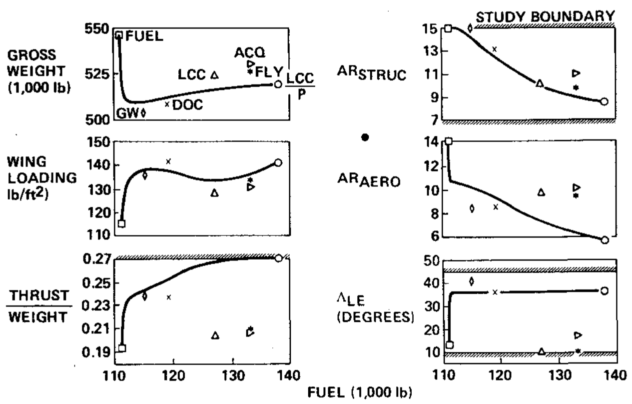

Fig. 5 Trade boundary characteristics.

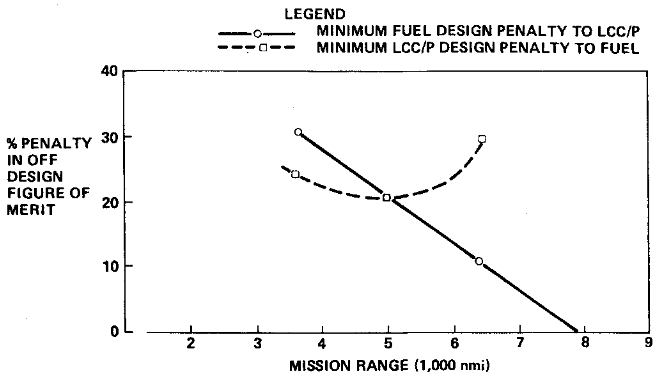

Fig. 8 Mission requirement effect on off-design figure of merit penalty.

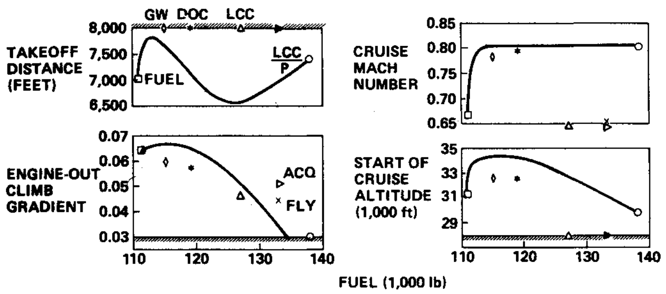

Fig. 6 Trade boundary performance characteristics.

LCC/productivity design and the value of 200 at the minimum fuel optima. If a compromise design between these two figures of merit were to be selected, it is important to understand the implications of trading penalties between them. It can be seen that most of the penalty in the off-design figure of merit is incurred in the last percentage reduction in the design figure of merit. A compromise design point can be achieved which keeps the penalty on each figure of merit to a small part of the full penalty. In fact, the minimum gross weight or minimum direct operating cost (DOC) designs are good compromise configurations for LCC/productivity and fuel.

There is a valley in the surface that allows these two designs to appear to be part of the basic trade family. On the other hand, the position of the other three cost optima emphasize the penalties incurred in the basic trade figures of merit by their selection.

Even though the minimum DOC design appears to be a part of the trade boundary on Fig. 4, its design characteristics are somewhat different, as shown on Fig. 5. The extreme position of the minimum fuel design is again emphasized. It is the only design that exceeds all of the secondary performance constraints of takeoff distance, cruise altitude, and engine-out climb gradient. The thrust/weight ratio is at the optimum value for minimum fuel with the wing configuration limited to the arbitrary study boundaries for structural aspect ratio and thickness ratio. However, it can be seen that the same wing swept to 36 deg requires less than 1% more fuel but reduces gross weight by more than 6% through the reduction in weight for a wing that poses less severe problems in gust response and flutter. That swing in wing leading-edge sweep also contributes to a pronounced change in takeoff performance, cruise Mach number, and cruise altitude as shown in Fig. 6.

The wing mean thickness ratio is at the minimum boundary value for the study ($t/c = 0.09$) along the entire trade boundary and initial cruise Mach number and altitude are limited by available thrust for maximum continuous operation for all designs on the boundary as well as for the other figure of merit design selections. Note that the cruise Mach number principally follows the influence of sweep angle, while cruise altitude and climb gradient are both influenced by aspect ratio as well as wing loading and thrust/weight ratio.

The extent of the compromise or trade region between two figures of merit is often a function of the mission requirement. For instance, the trade boundaries for minimum fuel and minimum LCC/productivity are defined for three values of mission range in Fig. 7; the leverage or magnitude of the shift in LCC/productivity between the boundaries diminishes and the leverage of fuel increases as range increases. The value of LCC/productivity along the minimum fuel boundary levels out at a value slightly less than $200/ton-mile/day. On the other hand, LCC/productivity along its minimum boundary increases with range and would, if extrapolated, reach the $200/ton-mile/day value at a design range near 8000 n.mi. At this point the trade surface becomes very flat and there is no penalty to LCC/productivity for selection of the minimum fuel design. Figure 8 shows the variation in the penalty to off-design figure of merit with

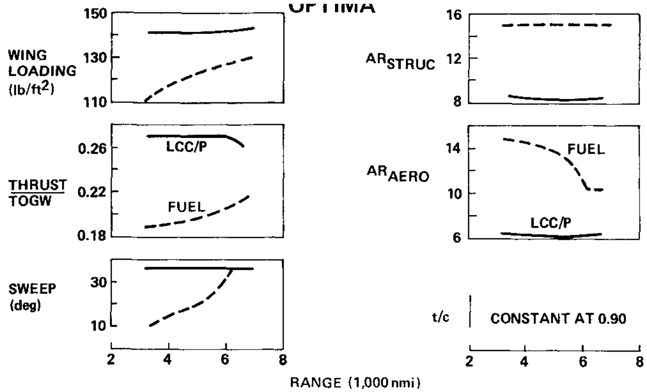

Fig. 9 Mission requirement effect on configuration optima.

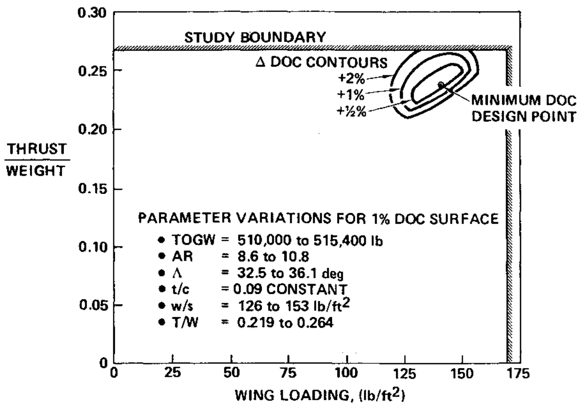

Fig. 10 DOC design sensitivity.

mission range and Fig. 9 shows that the configuration characteristics of the minimum fuel design tend to converge on the characteristics of the LCC/productivity design in everything except wing structural aspect ratio.

Another useful method of looking at the design surface is shown in Fig. 10 where the boundaries of designs within 1 and 2% of the minimum DOC design point are shown on a W/S, thrust/weight ratio plane. The object here is to illustrate the shape of the design surface relative to two of the most important design parameters. It must be kept in mind that the configuration along the boundaries has freedom to change and therefore conclusions cannot be drawn on the basis of the usual design selection "thumbprint." For instance, the takeoff requirement is not represented with a linear boundary. As the wing loading and thrust/weight ratio vary the wing planform compensates.

Conclusions

The design study procedure illustrated can furnish much deeper insight into the interaction of requirements, configuration, technology, and figures of merit with lower cost than traditional methods. Conclusions that are drawn from these data are as follows.

1) The differences in optimum design configuration are greatest between those optimized for LCC/productivity and fuel.

2) Configurations optimized to minimum gross weight and to direct operating cost impart the least penalty on off-design figures of merit.

3) Compromise configurations can be identified which are responsive to different weighting of the figures of merit.

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