33rd Wright Brothers Lecture

Size Effects in Conventional Aircraft Design

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As subsonic aircraft size has increased, the useful-load/gross-weight ratio has improved despite the so-called square/cube "law"; despite increasing requirements for such things as safety, reliability, and maintainability; and despite demands for greater comfort, speed, range, and productivity/dollar. Though future growth potential appears unlimited if adequate technology improvement time obtains, the economic advantage gain rate is flattening and further increases are likely in smaller increments. Nonetheless, one gross-weight doubling, and possibly two, is predicted by 1985; nuclear power can drive the optimum weight to 5 or 10 million lb before the year 2000.

I. Introduction

I WANT to express my feeling of gratitude and great humility at being invited to participate in this lecture series and thereby move into temporary proximity with men whom I have admired from a distance for so many years, starting with the Wright Brothers themselves and including the many eminent leaders of our field who have presented past lectures. I deeply appreciate this privilege.

One of my key impressions from reading about the Wrights is that of an extremely orderly, thorough, and systematic approach, coupled with their great broad-gage perspective as generalists. They appear to have been guided almost exclusively by this dedicated, careful, rational, and not particularly emotional discipline. They seem to have had all the qualities that we still admire and continuously work to develop today in our efforts to evolve progressively better aeronautical systems. They set a standard which we would do well, as integrators and synthesizers of such complex systems, to emulate.

Though earlier lecturers were apparently asked to hew to a particular technological line along which they were working at the time, and to avoid broad surveys, this prescription has been often violated, and to the benefit of aeronautics, by some very fine presentations rather more of the overview type. This paper responds to the request to treat the subject of the effects of increasing aircraft size, which is automatically of a survey nature.

In the belief that an interest in this area is probably keenest somewhere near the middle of the road with regard to missions and applications, the majority of the discussion and data are restricted to fixed-wing, subsonic, non-V/STOL machines, whether commercial or military, and generally to those designed as passenger or cargo transports. These limitations provide maximum order and trend consistency, and are judged to illuminate the vast majority of effects sought without proscribing their application to other mission types. The historical data used are biased toward incorporation of Lockheed data as a matter of ease and familiarity; reasonable, rather than exhaustive, efforts were expended for other data, and apologies are offered in advance for any errors in their use. For the purposes of this paper, where data scatter tends to be large, and trends and increments are more significant than absolute values, modest inaccuracies in historical data are considered acceptable.

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II. Overview

Definition

Before proceeding further, it is necessary to establish an acceptable definition of the word "size." Unfortunately, the vague catch-all notion of Webster: "physical magnitude, extent, or bulk" is generally accepted. This immediately introduces the multitude of common notions of linear dimension, area, volume, and mass; perhaps bulk even implies the possibility that, for two objects of identical dimensions and mass, the one with higher inertia about one or more axes is the bulkier and, therefore, of greater size.

In any event, the semantics of the issue can be settled with agreement that any or all of these physical measurements are significant and pertinent to the current purpose. Though linear dimensions are surely the most common root measure, and area and volume mere dependencies, mass requires independent treatment, as does inertia. This flexibility is exploited as necessary to explore the broad realm of size effects on aircraft design.

Historical Progression

It is instructive to examine the variation in four of these size measures from the Wright Flyer to the C-5A, generally accepted as today's largest airplane by virtually any measure. Figure 1 shows the historical (first flight date) variation in wing span, wing area, maximum gross weight, and moment of inertia in pitch—starting with the Flyer. The airplanes chosen are the "largest" by some measure in a given era, not including occasional aircraft of substantial dimensions apparently a little before their time, and characterized by light wing loading, high power loading, and insufficient useful load or speed. Where design data were unavailable, the inertias were computed using an empirical formula for radius of gyration of aircraft by J. P. Chawla.[1]

Two principal observations may be made. First, growth measured by linear dimension has been fairly steady, but with a flattening of the curves for wing span and area after 1930. Second, the really impressive changes in size occur only when

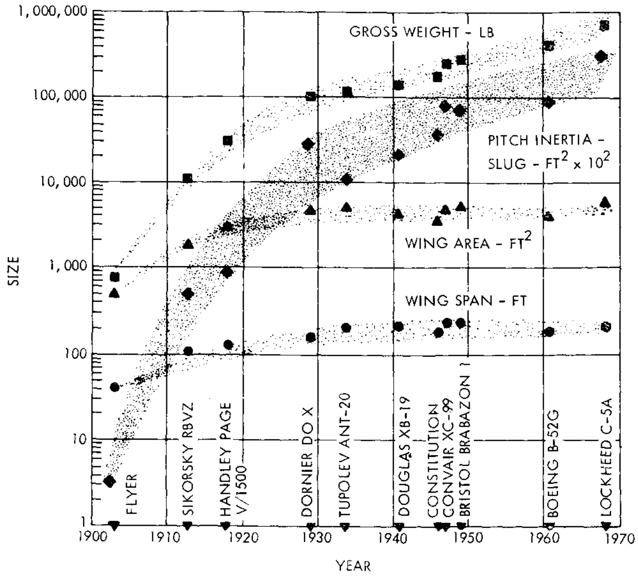


Fig. 1 Historical growth in size.

some measure beyond linear dimension is used as a criterion. Whereas the span of the C-5A is only six times that of the Wright Flyer, and the wing area is only twelve times as large, the gross weight increase is a factor of 1000, and the pitch inertia has increased by a factor of 100,000. This is in conformity with the precept of the square/cube law, discussed subsequently, that implies that size problems really arise from powers of linear dimensions greater than two.

Figure 2 shows that wing loading since the Wright Brothers has increased a hundredfold. Such growth, with attendant increase in structural efficiency, would have been impossible without the concomitant reduction in power-loading shown. These two parameters, together with usable maximum lift coefficient improvements, kept runway length requirements from becoming excessive.

Table 1 is a tabulation of data on these and a few other large aircraft. Statistics on some of these big aircraft are fascinating. The 1921 Caproni Ca 60 of Fig. 3 had 7696 ft^2 in its nine-wing configuration, but never flew successfully. To carry 100 passengers 410 miles, it used eight 400-hp Liberty engines and weighed 55,000 lb. The 106,000-lb Dornier Do X, powered by twelve 525-hp engines, flew in 1929 and established a world record by flying nearly an hour with a crew of ten, 150 passengers, and nine stowaways. Tupolev's 116,800-lb, eight-engined Maxim Gorki in 1934 had a wing area of 5233 ft^2 with a span of almost 207 ft.

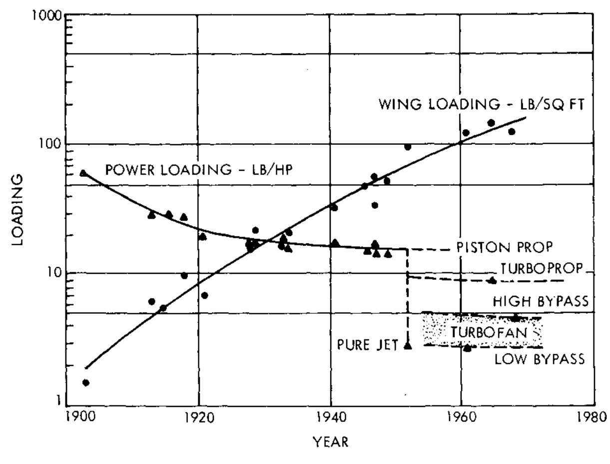


Fig. 2 Power and wing loading trends.

Square/Cube "Law"

If design philosophy and technology had remained static through the years, growth in aircraft size would have been halted by the square/cube "law." In essence, it states that the stress in similar structures increases with linear dimensions if the imposed load is proportional to the structural weight, since the latter grows as the cube of the linear dimensions and the material cross-section carrying the load grows only as the square. One can readily sense the rapid convergence of this projection to an ultimate limiting size of airplane at which the useful-load fraction disappears.

Even before man's powered flight, various individuals recognized the situation. Sir George Cayley[2] laid the groundwork for the modern square/cube law early in the 1800's. In 1935 the premises of this law were formalized in John Younger's textbook.[3] von Helmholtz[4] applied the square/cube law in the 1800's when he studied flying animals. His version is the straight line on the full log plot of Fig. 4, from von Kármán,[5] showing wing loading vs gross weight for a number of birds. Since the birds are all constructed of the same materials they—particularly the soaring class—follow roughly the line prescribed by the square/cube law.

Although the law applies most accurately and simply to nonliving objects with minimum structural loading interfaces with their environment, J. B. S. Haldane's article written in 1928 entitled "On Being the Right Size"[6] gave further fascinating insight into the realm of scale effects in zoology, showing that—and the second clause quoted sounds remarkably like a modern systems engineer—"For every type of animal there is a most convenient size, and a large change in size inevitably carries with it a change of form." He further touched closer to home when he pointed out that "An angel whose muscles developed no more power, weight for weight, than those of. . .a pigeon would require a breast projecting for about 4 ft to house the muscles engaged in working its wings. . ."

Perhaps one of the earliest authoritative statements on limitations of aircraft size was that by Professor W. F. Durand who, in his 1918 Wilbur Wright Memorial Lecture, saw no reason for aircraft size limit as long as the square/cube law could be kept in check.[7]

The load patterns of an airplane involve multivalued aerodynamic inputs which are also functions of linear dimensions squared; also, aircraft structure is sized and arranged by many considerations beyond a single steady-state static flight load case. No very simple application of the law should be attempted, therefore, even prior to the introduction of the many complicating contributions of advancing technology.

A short and tidy semiempirical treatment of square/cube first-order effects on aircraft characteristics appears in Ref. 8. Reference 9 approaches the subject somewhat differently, but extends the analysis to include cost effects—development, acquisition, and operating—to assess the likelihood of economically successful commercial transports carrying 1000 passengers or more. Both papers sound a note of caution based on trends in the past decade and a half, but admit that advances in technology will probably continue to permit "defeat" of the square/cube law.

It is tempting to apply a simple square/cube law projection over the range from the 750 lb of the Wright Flyer to the

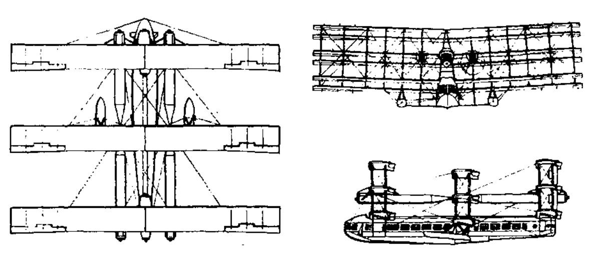


Fig. 3 Caproni CA 60.

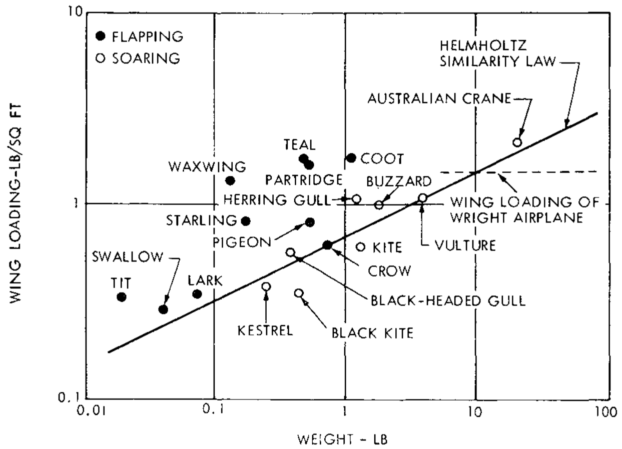


Fig. 4 Wing loading of birds.

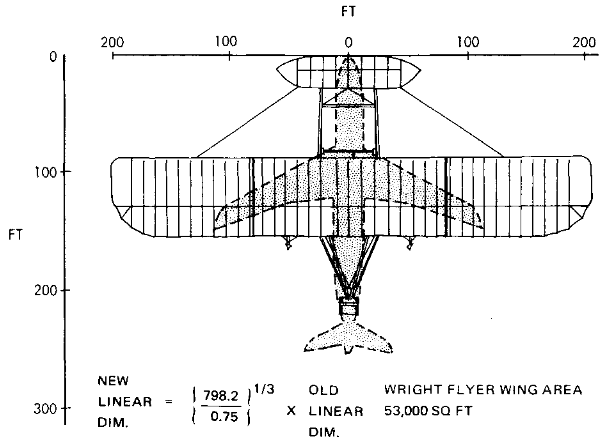


Fig. 5 The Wright Flyer extrapolated to C-5A maximum gross weight flown (square /cube extrapolation).

highest demonstrated takeoff weight of the C-5A, 798,200 lb. Figure 5 shows the result of that projection. Interestingly enough, the fuselage length projection is reasonably accurate. Considering the totally different structural and aerodynamic concepts involved, this similarity is strikingly coincidental. In the case of the wing, though, the projection is off by a wide margin. Whereas the 1903 technology extrapolated to 1970 requires a wing area of some 53,000 ft^2, current technology produces an airplane with 6200 ft^2. Similar comparisons may be observed in the horizontal trim surfaces.

Fortunately, technological advances have enabled consistently more progress than the square/cube law implies. To illustrate, the solid line of Fig. 6 charts the historical growth of useful load fractions for 23 representative aircraft, though only nine are designated. It is clear that progress has been substantial with the passage of time, particularly when the concurrent added improvements in speed and/or range, in passenger comfort or cargo flexibility, in safety, and in reliability and maintainability are recognized.

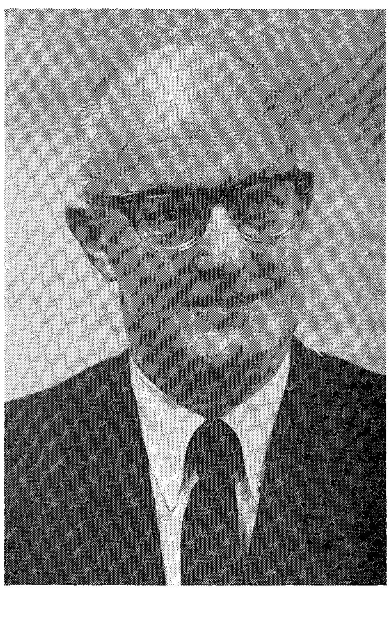
For comparison, the square/cube law projections based upon the then-existing state-of-the-art at the nine aircraft points are shown as dotted curves, or "isotechnology" lines. Each of the latter is extrapolated realistically to both higher and lower gross weights, including recognition of differences among primary and secondary structure weight percentages, base-point lift/drag ratio, and propulsion and other systemic technology of the time; each thus purports to portray what larger or smaller versions would have been, if designed simultaneously with the actual airplane. Though square/cube extrapolations from base-point aircraft may become unrealistic at large percentage variations in gross weight, the principle and trends are significant.

This presentation is intended to stick closely to size effects; since these are coupled to lift and drag aerodynamics only rather secondarily, compared to structures and weights, primary emphasis and content of the discussion are devoted to the weights of structures and functional systems. The major adversities of size arise there even though some direct influences, both helpful and troublesome, come through aerodynamics and propulsion. Thus, the aircraft useful-load fraction is a better criterion for the current purpose than some more complete, but also more complicated, one such as the product of speed, lift/drag ratio, and useful-load fraction.

The sources that have permitted the continuous divergences of Fig. 6 are manifold, but may be conveniently grouped into four sets, which are treated in detail in subsequent sections: 1) structural, including materials, design innovations, fasteners, and analytical capabilities; 2) aerodynamic, including both lift and drag parameters, and both internal and external flows; 3) propulsive, including fuels and systems as well as main engines; 4) systemic, including the host of subsystems providing flight control, secondary power, life support, and communication and navigation.

The separation of disciplines into these groups has the merit of orderliness, but militates against simple presentation of the interacting or synergistic relations whereby a tech-

F. A. Cleveland



F. A. Cleveland, elected vice president-engineering of Lockheed Aircraft Corporation in 1970, came to Lockheed in 1946 as an aerodynamics engineer. He became preliminary design group engineer in charge of the company's nuclear powered aircraft project in 1951 and was advanced to department manager, bomber design, in charge of the nuclear powered weapon system 125A program in 1954. In 1956, Cleveland transferred to the Lockheed-Georgia Company as preliminary design division engineer and two years later was promoted to chief advanced design engineer. He became assistant chief engineer and engineering program manager for the C-141 in 1961 and in 1964 was advanced to C-5 deputy program manager. In 1967, Cleveland was appointed Lockheed-Georgia Company vice president for advanced programs. He remained in that assignment until being elevated to his corporate vice president—engineering post in 1970. Cleveland received his A.B. degree in mechanical engineering in 1943, and his M.A. in aeronautical engineering in 1944 from Stanford University. He is a member of Tau Beta Pi (national engineering honorary fraternity) and is a former technical advisory committee member and national director of AIAA. Also he has been recently elected an Associate Fellow of AIAA.

Table 1 Largest aircraft examples starting with the Wright Brothers

Designer or manufacturer a. Model number b. Model name	1st flight date	Span, ft	Length, ft	Wing area, ft²	Gross weight, 1,000 lb	Empty weight, 1,000 lb	Useful load, 1,000 lb	Power plant, hp/thrust	Loadings: Wing lb/ft²	Loadings: Power, lb/hp or lb	No.[a] flown	Pax cap.	Range, ST.M.	Comment
Wright b. Flyer	12/03	40.3	21.1	510	0.75	0.6	0.15[b]	1 × 12 hp	1.47	62.50	1	0	...	Canard biplane & single engines driving two pusher propellers.
Sikorsky/RBVZ b. Ilya Mourometz	4/13	113	67.2	1,615	10.58	7.28	3.3	4 × 100 hp	6.55	26.45	80	16	300	Biplane with tractor engines on lower wing; used effectively as a bomber in W.W.I.
Zeppelin-Staaken a. VGO.1	4/15	138.5	78.7	3,572	20.99	14.38	6.61	3 × 240 hp	5.9	29.2	44	...	...	Biplane with one nose mounted engine & two wing-mounted pushers.
Handley Page a. H.P. 15(V/1500)	4/18	126	64	3,000	30	15	15	4 × 275 hp	10.00	27.27	10	40	1,300	Built to bomb Berlin in WWI; biplane with 2 × 2 tractor/pusher arrangement.
Caproni a. Ca 60 b. Transaero	1921[c]	98.4	76.9	7,696	55.12	30.86	24.26	8 × 400 hp	7.16	19.69	0[c]	100	410	Flying boat; triple triplane
Junkers a. G-38	11/29	144.3	76.1	3,229	44.09	28.66	15.33	2 × 400 hp 2 × 800 hp	13.63	18.33	8[j]	30	746	Engines wing-buried; DLH line service from 1932 to 1944.
Dornier a. Do X	7/29	157.5	131.4	4,736	105.8	72.2	33.6	12 × 500 hp	22.34	17.63	3	100[d]	850	Flying boat.
Kalinin a. K-7	8/33	173.9	91.9	4,887	83.78	53.79	29.99	7 × 750 hp	17.14	15.96	1	...	620	Bomber; projected 120-passenger transport version not built.
Tupolev a. ANT-20 b. Maxim Gorki	5/34	206.7	106.5	5,233	116.84	92.58	24.26	8 × 875 hp	22.33	16.69	2[e]	64[e]	1,240	Equipped with printing press and propaganda aerial loudspeaker system.
Douglas a. XB-19	6/41	212	132.3	4,285	162	75	65	4 × 2,000 hp	32.67	17.50	1	...	7,700	Bomber.
Lockheed a. 89 b. Constitution	11/46	189.1	156.1	3,610	184	114	70	4 × 3,000 hp	50.97	15.33	2	168	4,700	Full double-deck accommoda-tions
Hughes a. H-4(HK-1)	11/47	320.5	218.5	11,450	400	248	152	8 × 3,000 hp	34.93	16.67	1[k]	700	5,900	Flying boat; all wood.
Convair a. XC-99	11/47	230	182.5	4,772	265	140	125	6 × 3,000 hp	55.53	14.72	1	400	...	6 wing-buried engines with pusher propellers; full double-deck accommoda-tions.
Bristol a. 167 b. Brabazon 1	9/49	230	177	5,317	290	145	145	8 × 2,500 hp	54.54	14.50	1	100	5,500	8 wing-buried engines coupled in pairs to 4 tractor propellers.
Boeing a. YB-52 b. Stratofortress	4/52	185	153	4,000	390	166	224	8 × 10,000 lb	97.50	3.00[f]	744 (YB-52 and B-52G together)	...	7,000	Bomber.
Boeing a. B-52G b. Stratofortress	3/61	185	157.6	4,000	488	...	...	8 × 13,750 lb	122.00	2.85[f]		...	10,000	Bomber.
Antonov a. An-22 b. Antheus	2/65	211.3	189.6	3,713	551.2	251.4	299.8	4 × 15,000 hp	148.45	9.19	SP[g]	350[h]	6,800	High-wing, tail-loading cargo transport; contra-rotating propellers.
Lockheed a. C-5A b. Galaxy	6/68	222.7	247.7	6,200	764.5	320	444.5	4 × 41,000 lb	123.31	4.78[f]	SP[g]	1,000[i]	7,500	High-wing, nose & tail-loading cargo transport; T-tail.

[a] Counting original(s), subsequent series production, and derivatives—if any.
[b] Counting pilot (Orville Wright) and 5 lb of fuel.
[c] Destroyed in taxi-test which resulted in unintended liftoff.
[d] Set world record 21 Oct. 1929 with 169 onboard.
[e] One ANT-20 is built with six 1100-hp engines.
[f] Turbine energy expressed in terms of gas-hp with 0.8 efficiency.
[g] SP = in series production.
[h] Used mainly as freighter; 724-seat stretched version projected.
[i] Triple deck version.
[j] Two in Germany; six in Japan.
[k] Flew only once on high-speed taxi text.

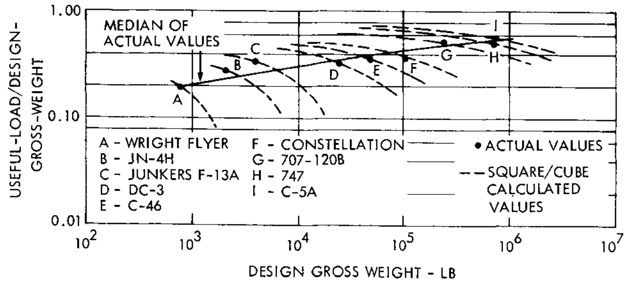


Fig. 6 Useful load fraction—historical and projected.

nological advance in one area permits an advance in another area not otherwise possible. Since the single steps themselves are somewhat troublesome to collect, their interactive progress would be even more difficult to reconstruct; the original criticism is thus ameliorated and its acceptance made more tolerable. In the final "projections" section, where possible futures are considered, interaction can be handled more easily and so appears there.

Partially in consideration of these interactions and partially to clearly separate fact from fancy, the sections of the paper prior to the final one deal generally with the effects of aircraft size within a discipline, in theory when possible, and as demonstrated by actual data in any event. Thus, they are intended in the main to reach only to the present, though some forecasting is included directly or by implication. Since the future flows from the past, this provides a foundation for the predictions to follow.

Except for occasional references to it, costs are reserved principally for the section so titled; the five sections to follow aim principally at technological progress to date, without much consideration of justification of the process in economic terms. This is again a matter of convenience but tends to de-emphasize the vital economic element of aircraft design; such intent should not be inferred.

Changing Requirements

One other set of factors is of significance to the analysis of size evolution, but it is of rather different character: the specifications, regulations, and requirements to which aircraft are designed have changed steadily over the years. These changes have been, in the aggregate, in the direction of greater safety, performance, and operational flexibility, and have thus acted generally as constraints on size increases additional to the square/cube law. Typically, each new requirement has reflected recognition in a previous design of a condition where correction was essential or highly desirable, or recognition of an added performance capability which advances in technology permitted and an operator demanded.

Generally speaking—and not including the basic performance items such as speed, range, altitude, payload, and field length—the requirements which have evolved beyond the simple task of lifting a single individual in 1.0-g powered flight in good climatic conditions for a brief interval can be categorized as follows: Safety by redundancy: engines, controls, systems, structure; Personnel and equipment environment: pressure, temperature, acoustics, fire-protection, illumination; Materials: strength, fatigue, corrosion, wear; Operational: ground maneuvering, stability, control effectiveness, climb capability, noise.

Figure 7 portrays qualitatively the chronological growth of some of the major requirements. One of the latest elements which may have a rather profound effect on size in the future is the new Federal Aviation Regulations Part 36 dealing with fly-over noise levels. Figure 8 shows that this requirement recognizes size growth up to a point, but above gross weights of 600,000 lb it fixes a flat limit of acceptable noise levels which, at the present state-of-the-art in noise-suppression

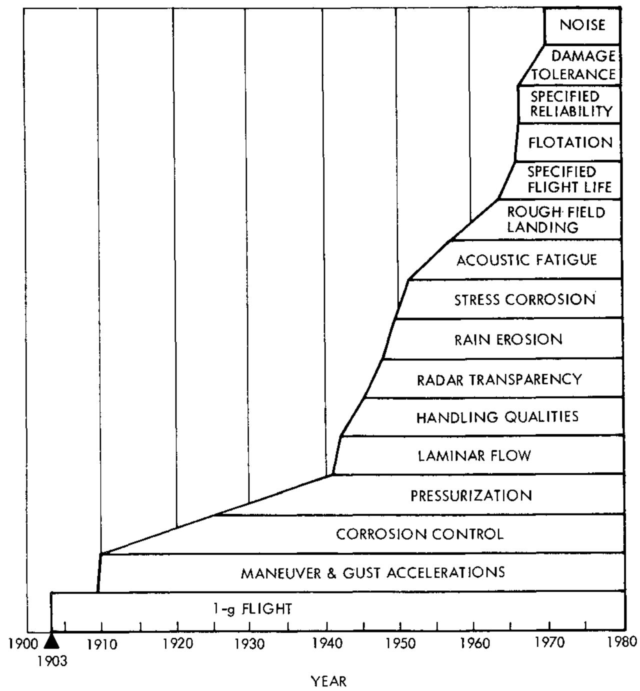


Fig. 7 Design requirements development.

techniques, seems to pose a severe problem for some of the large airplanes of the future.

Another interesting case wherein the problems of designing large aircraft have been amplified by tightening requirements lies in the area of handling qualities. Flight control system breakout forces and stick forces normally increase with the size of the aircraft. In the C-5A, however, the requirement was for a breakout force substantially reduced from previously acceptable values, reflecting the customer's desires for improved handling qualities regardless of the normal trend with size.

Another requirement which is particularly significant for large aircraft is imposed by the airport interface. Substantial concessions are made in design to insure compliance with military and civil runway and taxiway flotation limitations. Figure 9 depicts the flexible pavement thickness requirement as a function of aircraft gross weight, computed by the method of Ref. 10 for soil of California Bearing Ratio 15. Above approximately 450,000 lb, multiple tire/strut arrangements, with attendant weight penalties, have been employed to meet the flotation capabilities of existing runways.

The C-5A value illustrates an extreme in current flotation capability. The fact that it falls so far below the curve is

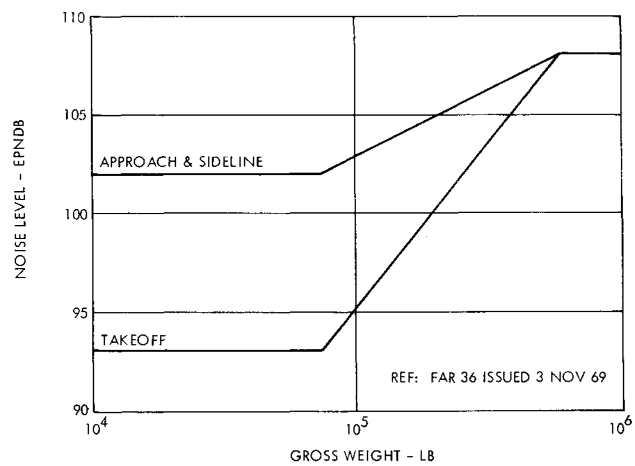


Fig. 8 FAA noise limits.

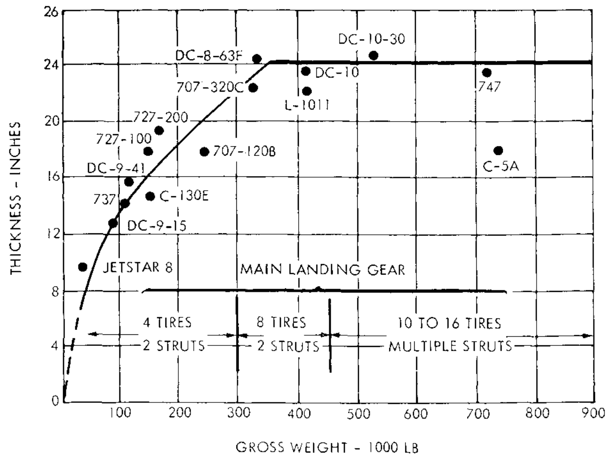


Fig. 9 Flexible pavement requirements (CBR 15 subgrade).

because of the specification that (at lighter weights than that plotted) it be operable from unprepared strips.

Additionally, in meeting flotation requirements by multiple strut and tire design, new problems of gear scrubbing in turns are generated. Steerable main landing gear systems may be employed to avoid excessive side loads, improve turn radius, and reduce tire wear from scrubbing.

Although the influence of ever more demanding requirements has been treated only briefly here, their substantial impact on empty weight relative to that of any prior design should be kept in mind.

III. Structures

A combination of increased analytical and testing sophistication, improved materials, production innovations, and imaginative design concepts has contributed substantially to increasing aircraft useful-load fraction with time. This has been achieved in spite of more demanding requirements and progressive increases in size with concomitant square/cube trends and increasingly severe aeroelastic effects. Before elaborating, it is instructive to examine, at a fixed state-of-the-art, the basic relationships of strength, stiffness, and material properties with increasing size.

Structural Scaling

If a wing is scaled while holding constant the relative geometry, wing loading, allowable stresses, and ultimate load factor, it can be shown by statistical means that the wing weight will vary approximately as the airplane gross weight to the 1.4 power. This value approaches the square/cube result of Ref. 7, using a simple beam analogy. The slight deviation occurs mainly because the strength/density ratio of structural materials tends to increase with size, as will be discussed later.

The relationship between the fuselage weight and gross weight, however, does not follow the square/cube law in large transports when the fuselage is scaled up while holding the cargo density, length/diameter ratio, allowable stress, internal pressure, payload/gross-weight and landing-weight/gross-weight ratios constant. If a hypothetical aircraft A, at 320,000 lb is scaled up to twice that gross weight under these constraints to become aircraft B, the fuselage weight is related to the ratios of fuselage surface areas and of gross weights. When the density of the payload and the payload/gross-weight fraction are constant, the fuselage surface area varies as the gross weight to the $\frac{2}{3}$ power. If fuselage weight is plotted against fuselage surface area, statistical data show that the fuselage weight varies as surface area to approximately the 1.32 power; hence, the fuselage weight will vary as gross weight to the $1.32 \times \frac{2}{3}$, or about the 0.88 power, as plotted in Fig. 10.

The component weights of the two hypothetical transports are compared in Table 2. The wing loading, relative geometry, density of payload, and performance are constants. The component weights are based on statistical weight equations which were developed for each of the major airplane components and types of equipment. The statistical base of the weight equations is composed of 35–40 airplane models, which includes most of the large U.S. airplanes built within the past 25 years, but the uncertainties of such statistical derivation are recognized.

As might be expected, there is a considerable diversity of scaling among components. This is particularly apparent between the airframe components where the square/cube law has a strong influence, as on the lifting surfaces, and those where it has little effect, as on the fuselage. The landing gear, power plant, and airconditioning system tend to increase approximately as gross weight, but the electrical system, electronics, instruments, ice protection, and furnishings are affected more by mission requirements than by aircraft size. On balance, the over-all factor of about 2.1 reflects the tendency of the square/cube law to project a modestly increasing structural weight fraction with size.

Figure 11 illustrates how the weight fractions of the major components vary with gross weight. While the comparison of Table 2 is based specifically on airplanes of 320,000 lb and 640,000 lb gross weight, the trends which are indicated should be of general applicability, since the gross weights of the

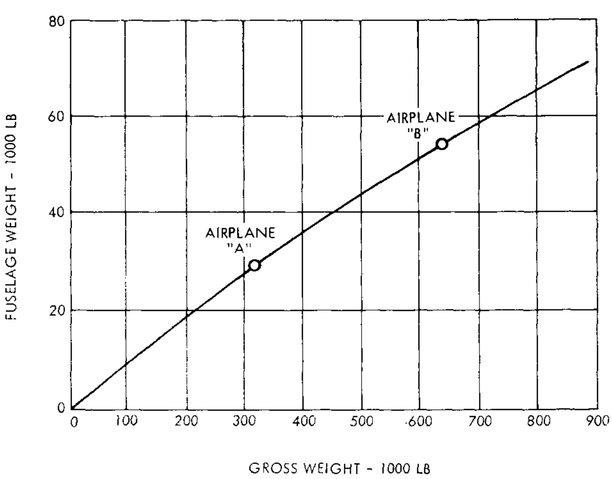


Fig. 10 Fuselage weight growth.

Table 2 Comparison of component weights

Item	Airplane A	Airplane B	B/A
Gross weight	320,000	640,000	2.00
Payload	80,000	160,000	2.00
Empty weight	131,200	277,125	2.11
Wing	35,000	94,000	2.69
Fuselage	29,300	54,000	1.84
Empennage	5,700	13,250	2.33
Surface controls	3,650	7,750	2.12
Landing gear	10,800	21,600	2.00
Hydraulics	1,350	2,250	1.67
Power plant	30,300	62,700	2.07
Instruments	1,130	1,550	1.37
Electrical systems	3,000	4,200	1.40
Electronics	2,450	2,950	1.20
Air conditioning	2,550	5,070	1.99
Furnishings	5,000	6,300	1.26
APU	520	880	1.69
Ice protection	450	625	1.39

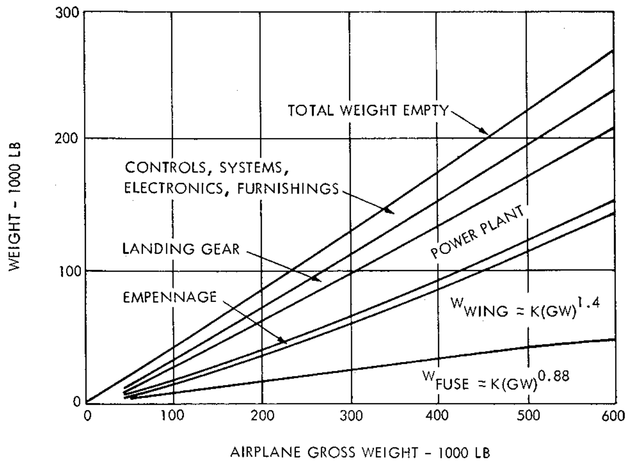


Fig. 11 **Component weight variation with gross weight.**

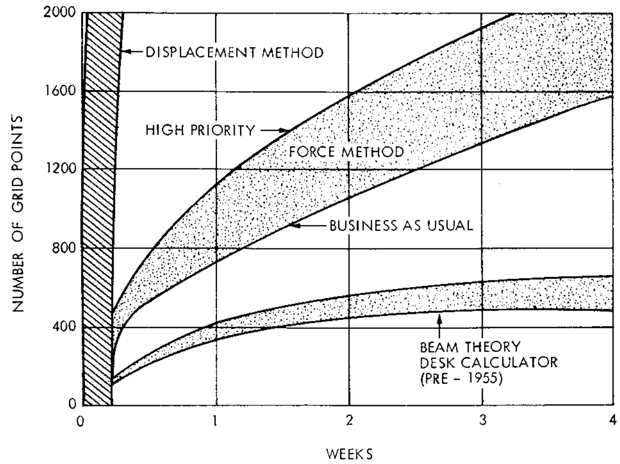


Fig. 12 **Internal loads analytical complexity tradeoff with time required.**

airplanes in the statistical base of the weight equations range from 20,000 to 728,000 lb.

Analytical Methods

A primary reason for the evolution of progressively more efficient structures has been the development of new analytical methods. As structural concepts have evolved from single-spar unswept wings to multispar swept wings, for example, the complexity of analysis necessary to achieve the required increasingly high level of confidence has grown dramatically. Too, growth in size of airplanes has meant more parts, more fasteners, and more analysis even if sophistication had not increased at all. At the same time, the development period of airplanes has tended to remain relatively constant, even though the effects of size might reasonably be expected to demand longer times.

Fortunately, the combination of the advent of high-speed computers, the evolution of improved insight into the mechanics of structures, and the development of advanced analytical techniques has enabled the stress analyst to meet these contradictory complexity and schedule requirements. The tremendous capacity of modern computers to handle matrix operations opened the way for extensive use of redundant analysis techniques in stress analysis of complex structures. These methods not only meet the requirement for more exact analysis, but the elapsed time needed to accomplish the analysis has also been shortened.

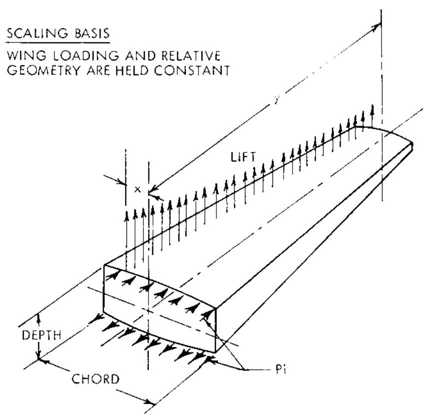
Figure 12 depicts the number of grid points utilized to represent the structure vs the calendar time needed to conduct an internal loads analysis, and illustrates several points. First, the pre-1955 beam-theory approach had capacity for only 500 – 600 grid points, limiting its accuracy for anything but relatively simple structure. Second, the tremendous reduction in time shown between the first-generation force methods and the more recent displacement methods is clear. The example chosen, that of internal loads computation, is obviously within the context of a single operation conducted in structural analysis. Similar results are to be found throughout the entire analysis spectrum.

Materials

A larger aircraft tends to be able to utilize the available strength of materials more efficiently than a smaller one. Consider again the simplified wing box with structure optimized for a given aircraft gross weight, then scaled up, using the same relative geometry and constant wing loading, to twice the gross weight and payload. The loading intensity at the root of a box beam is approximately equal to the root bending moment divided by the cross-sectional area of the box. Figure 13 shows the derivation of the loading intensity in the box beam and its variation with size.

Figure 14 shows the relative increase in specific strength, F_c/ρ, of such wing families with increased load intensity. The figure shows that, if the loading range for wing B is considered as representative of today's jumbo jets, the loading intensity near the upper end of the range indicates that a titanium wing would weigh little more than an aluminum one. Beyond this aircraft size, such denser materials could be stabilized to support compression loads approaching their ultimate compressive strengths, resulting in lighter-weight wing boxes than aluminum. For this reason, the material weight in a wing box increases somewhat more slowly than the gross weight to the $\frac{3}{2}$ power.

The truly impressive developments in aircraft materials are illustrated in Fig. 15 by a comparison of the materials available in 1903 with those today. The increase in modulus of elasticity reflects response to the increasing requirements for stiffness, so important in the design of large airplanes. The true evolution of stiffness is only partly reflected in these modulus numbers. Improved concepts, such as integrally stiffened shapes and many varieties of reinforced con-



ITEM	AIRPLANE A	AIRPLANE B
GROSS WEIGHT	1	2
PAYLOAD	1	2
CHORD OF BOX	1	$\sqrt{2}$
DEPTH OF BOX	1	$\sqrt{2}$
DEPTH X CHORD	1	2
BENDING MOMENT = f(LIFT, y)	1	$2\sqrt{2}$
P_i = SURFACE LOADING* INTENSITY $\approx \frac{\text{BENDING MOMENT}}{\text{DEPTH X CHORD}}$	1	$\sqrt{2}$

*(AXIAL LOAD PER INCH IN SURFACES OF WING BOX BEAM)

Fig. 13 **Effect of wing box size on loading intensity.**

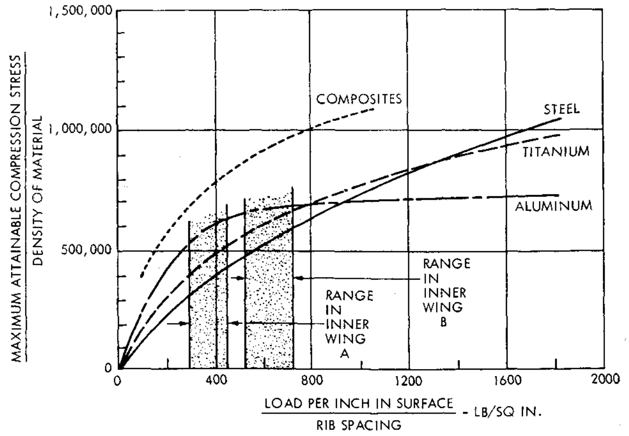


Fig. 14 Effect of loading intensity on stress/density ratio.

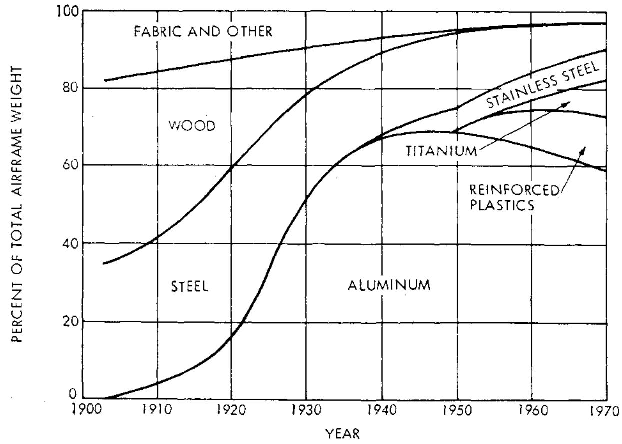


Fig. 16 Historical variation of aircraft material usage.

struction, are highly efficient in resisting buckling and other specific types of deformation, contributing to lightweight design more rapidly than the modulus increases alone.

Figure 16 shows the approximate percentage of utilization of various materials since 1903. For some twenty years after man's first flight there were few changes; primary reliance was on fabric and steel or wood frame construction. It is estimated that the structural materials used in the Wright Flyer I consisted of 18% fabric, 47% wood and 35% steel by weight. By 1915, however, Junkers in Germany had produced the first successful all-metal airplane.

Wood, which at one time was a staple of the materials list, has been virtually phased out, existing today only in furnishings and to a very limited degree. Reinforced plastics are a recent and rapidly growing addition to the list, having nearly taken over the trim field, and finding widespread use in secondary structure as well, particularly where acoustically induced fatigue may exist. Although available for over 20 years, titanium has only recently come into favor in subsonic aircraft. Its increased usage has been partly the result of decreasing cost and partly because of the loading factors illustrated in Fig. 14.

Mostly, however, the material contribution to lighter design has come from a steady expansion of the capabilities of aluminum and steel. High-temperature materials technology has provided some fallout to the type of vehicles addressed in this paper, but in highly specialized and limited applications. The use of beryllium and carbon for brake heat sinks is a good example. Typically the really exotic materials continue to be difficult to justify economically.

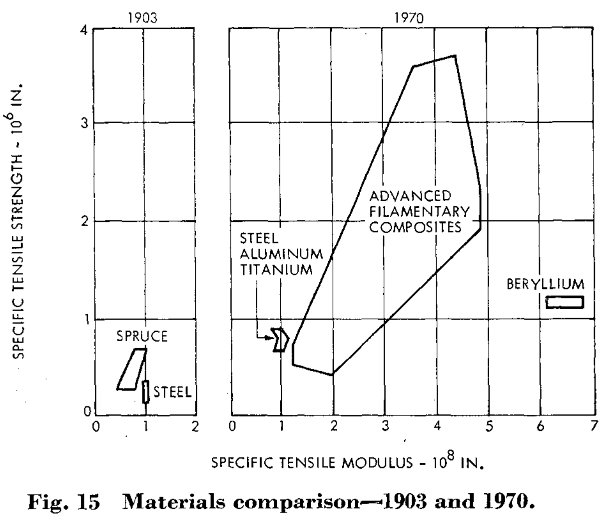


Fig. 15 Materials comparison—1903 and 1970.

Joining

From the inception of powered flight, joining methodology has remained a paramount concern. In the early fabric-covered aircraft, the problems centered around the fastening of the metallic or wooden frame members to each other by mechanical fasteners, glue, welding, or other means.

The scope of the fastening problem broadened considerably with the advent of stressed-skin design. Because of the great increase in number of fasteners, the degree of conservatism previously employed was no longer tolerable. Bolts and aluminum rivets produce a three- to five-fold increase in the local stress, a most significant factor in both the static and fatigue strength of the joint. Submergence of the fastener heads within the aerodynamic contours to minimize drag results in further degradation of fastener efficiency by the reduction of both the pull-through strength and the clamp up of the joint, because of the tendency to produce knife edges in the sheet. The large number of fasteners and holes increases fatigue suscepTbility.

Intensive development over the last 10–15 years in higher strength fasteners has brought the technology to relatively small diameters, helping to avoid much of the secondary weight penalties caused by providing pad-up of the base material at the fastener location to offset the increase in local stress, and by providing wide flanges to preclude shear-out. More recently the importance of prestressing of the material surrounding fastener holes has been recognized, and interference-fit fasteners have appeared to exploit that feature.

The impact of evolving fastener technology on the direct and indirect weight of the fastener system in today's large vehicles is quite substantial, as Fig. 17 shows. Here a projection is made from the 24,000-lb. DC-3 of Ref. 3, assum-

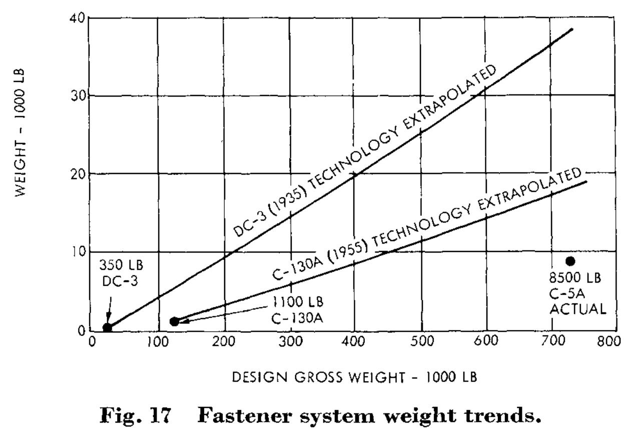


Fig. 17 Fastener system weight trends.

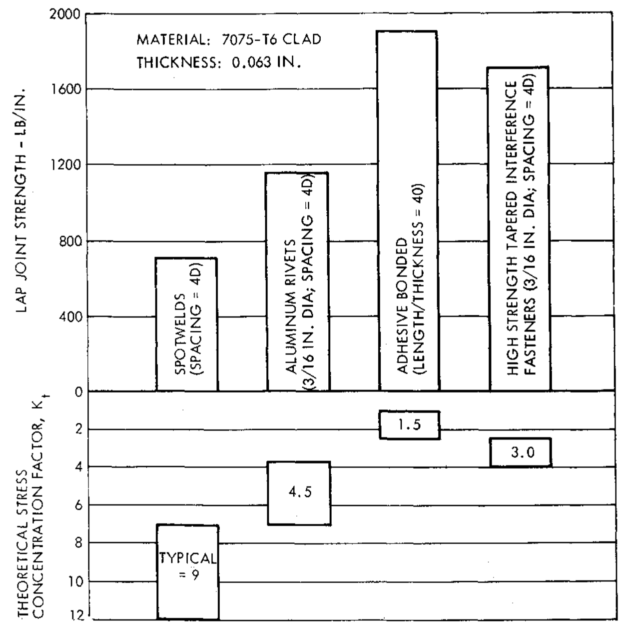


Fig. 18 Joint strengths and stress concentration factors for common fastening methods.

ing none of the advances just discussed. The DC-3 used a stressed skin and stringer type of construction similar to that used today except that the skins were lapped and fastened with low strength, protruding-head rivets and bolts. This approach would result in a C-5A fastener-system weight of 38,500 lb. The actual weight, by comparison, is only 8500 lb. A similar projection of the C-130 shows a comparison at an intermediate state-of-the-art.

There is an increasing utilization of bonded joints. Accelerated by the increasing usage of nonmetallic structures, bonding has a great deal to offer to metallic structures as well, particularly for minimum weight in applications where fatigue is critical, low-load intensities predominate, avoidance of fastener stress concentrations is important, surface smoothness is significant, and/or certain sealing requirements exist. A primary constraint remains the difficulty of unarguable assurance of positive joining. Although X ray, ultrasonic, and coin-tapping techniques, while able to indicate a flaw in the bond line, do not provide positive indication of the nature of the flaw and therefore of joint integrity, a great deal of satisfactory service life continues to accumulate in most cases. The addition of a full complement of mechanical fasteners for static strength in critical locations in primary structure eliminates any hazard from inspection uncertainty.

A simple summary of the salient features of several of the current joining methods is given in Fig. 18. The chart includes spotwelding in addition to those techniques just discussed, although this method is used sparingly at present due to its rather higher susceptibility to fatigue and, in some cases, to corrosion.

Damage Tolerance

The necessity of providing a quantified useful-life goal for an aircraft has become one of the dominant structural design criteria. Aircraft were generally designed for static and dynamic loads, and the structure tended to be of the builtup type, until the late 1950's; sufficient fatigue resistance inherently resulted, dramatically illustrated by the longevity of the DC-3 fleet. But the dynamic response characteristics of large aircraft, combined with the higher design stress levels in today's high-strength metals, produce a potentially more damaging spectrum of repeated stresses. In the indirect sense, the tremendous capital investment that large modern transports represent, along with the sizable percentage of a fleet's total capability which may be represented by a single airplane, places a high premium on maximum utilization of all aircraft. Thus, standards of reliability that were acceptable in large fleets of smaller aircraft are not high enough for relatively small fleets of very large aircraft.

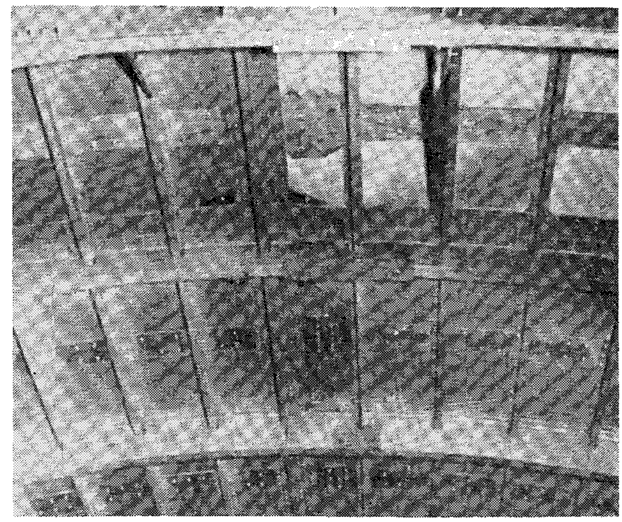


Fig. 19 Damage-tolerant design concept.

The effect of size on the number of passengers per aircraft has resulted in increased concern for safety and reliability by the airframe manufacturers and operators, the regulatory bodies, and the public, so that damage tolerance has emerged as a primary design consideration. Figure 19 shows a typical damage-tolerant design concept utilizing thin titanium straps installed midway between the fuselage rings, such that a skin crack advancing from an adjacent failed ring will not propagate further, and the airplane can continue to operate until a repair is made.

At the same time, operators are demanding more stringent fatigue assurance. Figure 20 shows that, in terms of the number of flights, some of the targets under discussion impose flight numbers that are only currently being reached in service by some of the older airplanes. The requirement to provide a long and trouble-free life poses one of the most severe design challenges, particularly for large aircraft. Despite intense activity on fatigue mechanisms and analysis in recent years, the accuracy of calculating even the average time to cracking is still not satisfactory.

Stiffness

Adequate stiffness to control adverse aeroelastic phenomena is as significant as the static strength required. Bending stiffness and torsional stiffness are the primary parameters for structural rigidity. These are closely interrelated and control

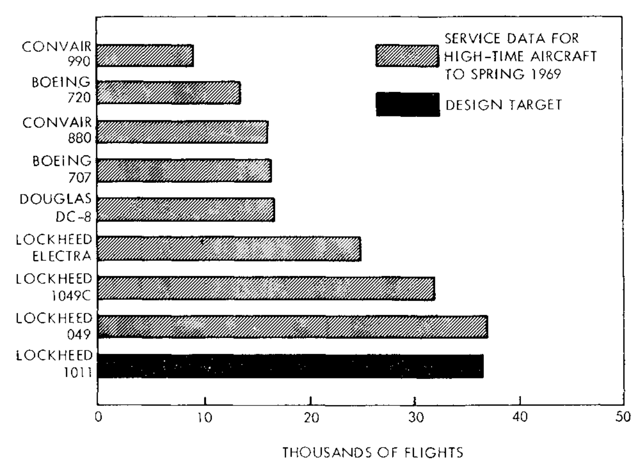
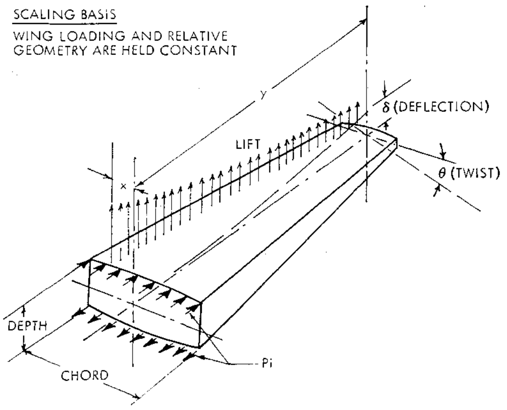


Fig. 20 Airplane utilization.



ITEM	AIRPLANE A	AIRPLANE B
GROSS WEIGHT	1	2
PAYLOAD	1	2
CHORD OF BOX	1	$\sqrt{2}$
DEPTH OF BOX	1	$\sqrt{2}$
DEPTH X CHORD	1	2
BENDING MOMENT f(LIFT, y)	1	$2\sqrt{2}$
TORSION = f(LIFT, x)	1	$2\sqrt{2}$
P_i - SURFACE LOADING INTENSITY $\approx \frac{\text{BENDING MOMENT}}{\text{DEPTH X CHORD}}$ (AXIAL LOAD PER INCH IN SURFACES OF WING BOX BEAM)	1	$\sqrt{2}$
$J \approx \frac{4A^2}{\oint \frac{ds}{dt}} \approx \frac{4\,(\text{DEPTH X CHORD})^2}{\text{PERIMETER/SKIN THICKNESS}}$	1	4
I - MOMENT OF INERTIA $\approx$ THICKNESS OF SKIN X C X $\frac{d}{2}^2$	1	4
θ = TWIST $\approx \frac{\text{TORQUE X y}}{GJ}$	1	1
δ = DEFLECTION $\approx \frac{My}{EI}$	1	1

Fig. 21 Effect of box size on loading intensity, deflection, and twists.

the deflection and twist in a wing box, for example. It is desirable that the relationships between the deflections and twists be held constant in spite of increased size.

Structural weight increments which are added to provide adequate stiffness in a wing box do not increase, as a percentage of box weight, with size because the material added for strength increases as gross weight to about the 1.4 power, keeping the relative deflections constant in spite of the dimensional increases. Figure 21 compares the loading intensity, deflection, and twist of two wing boxes for the same conditions as Fig. 13. The inference is that the weight added for strength maintains constant relative deflections.

As aircraft become larger, however, some effects of structural flexibility become more pronounced. For example,

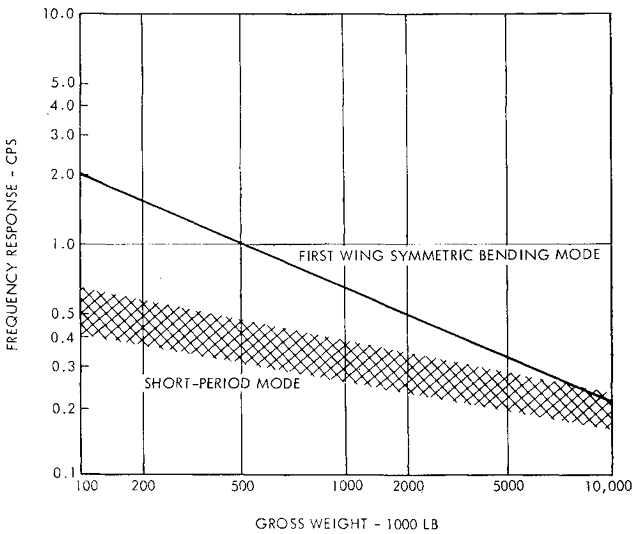


Fig. 22 Swept wing bending and short-period response.

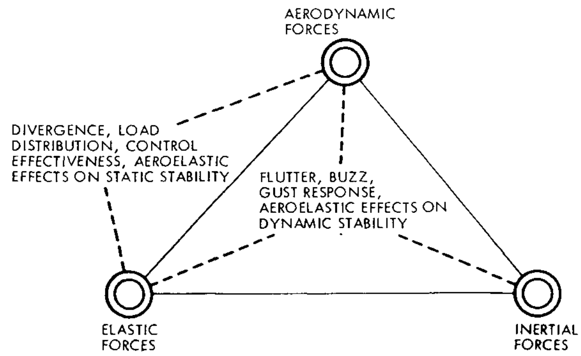
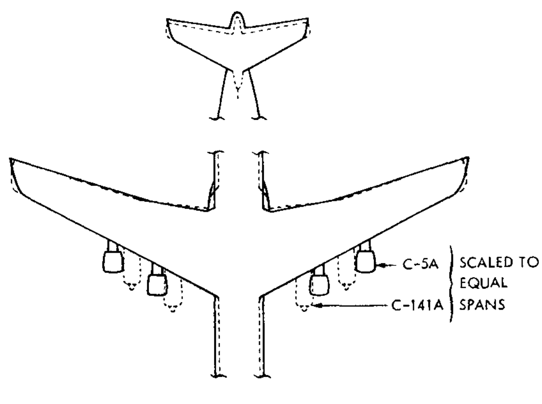


Fig. 23 Aeroelastic triangle.

problems arise when the first wing symmetric bending frequency and short-period aircraft frequency approach each other, as indicated in Fig. 22. When an aircraft encounters a gust, the resultant wing bending induces motion of the aircraft. If this frequency is coincident with that of the short-period mode, a new problem appears. In attempting to damp out what appears to be the aircraft short-period oscillation, the pilot may well intensify the wing bending, which was the original cause of the motion. In addition, these frequencies are in a range in which motion sickness and amplitude-dependent human response factors are most pronounced.

An apparent solution to this problem lies in the application of devices, such as a Stability Augmentation System (SAS) or the recently-investigated Load Alleviation Modal Suppression (LAMS) system and the Identical Location of Accelerometer and Force (ILAF) system. These possess the primary advantage over the human pilot of having virtually zero response lag, and having tailored response characteristics. Other possibilities include the application of materials with superior specific moduli, such as graphite or boron, to provide greater stiffness, or a change in the design to a lower aspect ratio.



MODE	C-141A FREQUENCY (CPS)	C-5A FREQUENCY (CPS)	C-5A/C-141-A
SYM. 1ST BENDING	2.49	2.0	0.80
SYM. TORSION	3.89	2.69	0.69
SYM. BDG-TORSION	4.25	2.84	0.67
SYM. 2ND BENDING	5.30	3.56	0.67
ASYM. 1ST BENDING	1.95	1.58	0.81
ASYM. TORSION	2.48	2.2	0.89
ASYM. 2ND BENDING	5.89	5.15	0.88

Fig. 24 C-5A/C-141A frequency comparison (zero fuel).

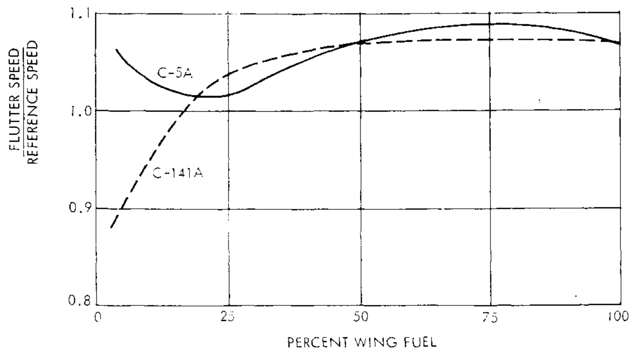


Fig. 25 C-5A/C-141A wing flutter comparison.

Dynamic Response

The dynamic response of the structure is dependent upon the aerodynamic forces of excitation, upon the elastic structural restoring forces, and upon the inertia forces of the structural mass in motion. This aeroelastic triangle, illustrated in Fig. 23, governs aeroelastic phenomena, as indicated in Ref. 11. Successful design maintains these in proper balance and provides sufficient structural and aerodynamic damping to preclude divergent oscillation. Phenomena dependent upon these elements are flutter, control-surface buzz, gust response, and aeroelastic effects on dynamic stability. Other phenomena which have little or no dependence upon inertia forces, but which are strongly linked to the remaining two elements of the triangle, are divergence, load distribution, control effectiveness, and aeroelastic effects on static stability.

Generally speaking, as the size of the vehicle increases, the relationships among the forces in this triangle tend to shift and rebalance. Although the mass is increased, the frequency of oscillation is normally decreased sufficiently that the product of mass and acceleration is essentially constant. Redistribution in the triangle force balance does not automatically lead to less satisfactory airplane stability; no strong generalizations can be derived.

In the specific case of flutter, aircraft growth effects defy precise quantification. This is particularly true with movable surface involvement, where more than three-quarters of recorded in-flight instabilities have occurred. For example, the square/cube law indicates that the flutter speeds are identical for large and for small geometrically similar aircraft, both fabricated of the same material. Even where this geometric similarity is fairly close, however, as in the C-141A and C-5A comparisons of Fig. 24, differences in modal frequencies do exist. These are primarily due to differences in engine location and the nonscaling of the engine weight. The similarities of the flutter speeds of the two aircraft are illustrated in Fig. 25. The comparison is close except for the conditions with very little fuel, where the effect of the engines becomes predominant and changes the flutter-speed ratio.

Gap Tolerance

Increased absolute structural deflections, generally inherent in larger aircraft, complicate the close control of gaps and slots in high-lift devices where the amount of lift generated is closely dependent on the slot geometry. On the outboard wing leading-edge slats of the C-5A, for example, the tolerance in slot gap between the slat trailing edge and the wing fixed leading edge, as illustrated in Fig. 26, is 0.1% of the local wing chord, or about 0.37 in. at the mean aerodynamic chord of the wing. It is obviously not feasible to maintain such tolerances with a single slat when the 1.0 *g* static wing deflection is of the order of 50 in. in the wing semispan. While the slat could be forced to assume the same deflection as the wing, such an approach is quite heavy due to multiple hinges, actuation complexity, and induced slat bending. A better approach for holding the differential deflection between a single slat and the associated wing span within acceptable tolerances is to segment the slats, as illustrated in Fig. 27. The C-5A uses the segmented approach on the flaps and other control surfaces, as illustrated by the trailing-edge flaps in Fig. 28, whereas a smaller airplane like the DC-9 can meet its requirements with a single-segment flap.

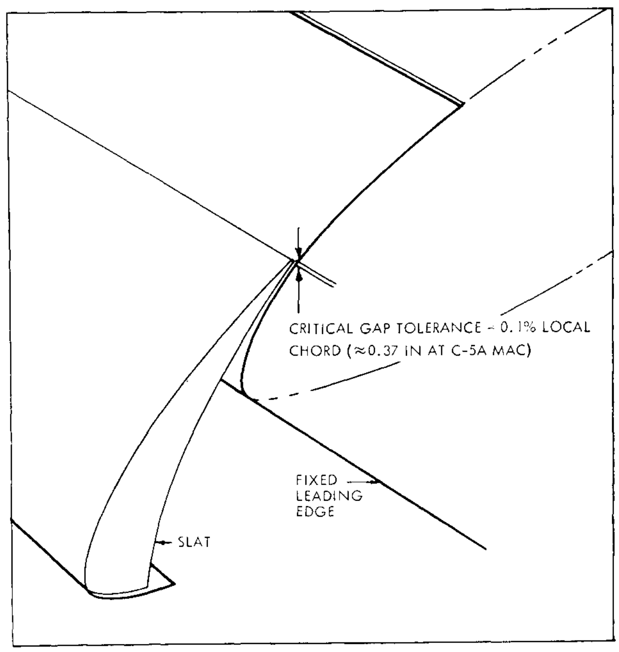


Fig. 26 Critical slot tolerance for C-5A wing leading-edge slat.

Other problems which are significantly affected by increased structural deflections include those related to pressure seals; aerodynamic drag due to gapping, rigging, and latching; and interference of movable surfaces and doors. The rigging problem is particularly difficult in large aircraft requiring provisions for numerous adjustments in torque tubes, actuating arms and functional equipment. Problems associated with ground clearance for wing tips and wing-mounted engine pods are magnified by the increased deflections of larger aircraft, especially during accelerated ground-turning maneuvers. Provisions in ground support equipment must allow for the greater absolute differences in height above the gound for weight variations from empty to the maximum gross weight, and for power assist in handling heavy components.

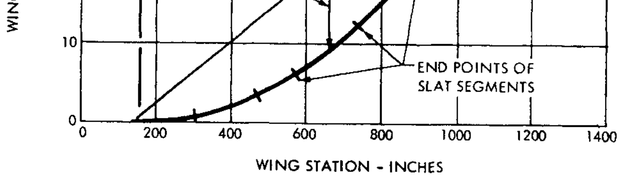


Fig. 27 Effect of slat segmentation on differential deflection.

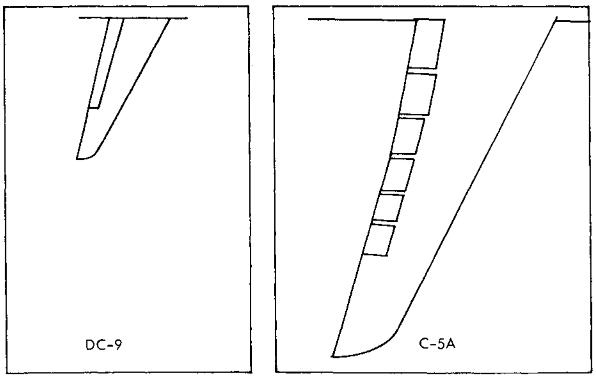


Fig. 28 DC-9 and C-5A flap arrangements.

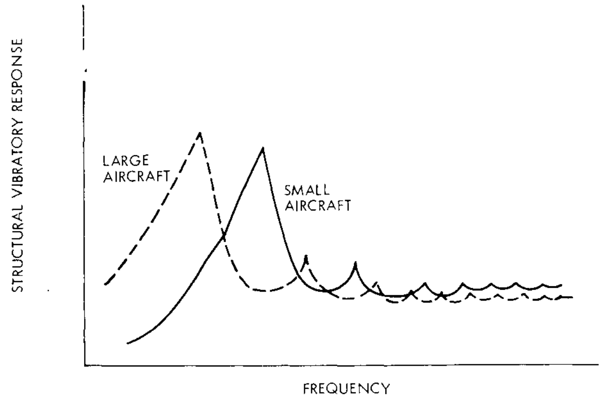


Fig. 30 Vibratory response of fuselage sidewall.

Interior Noise

The size of an aircraft fuselage has a noticeable effect on interior noise levels during cruise when aerodynamic noise predominates. Propulsion noise during cruise is usually not heard in aircraft that have engines hung on pylons under the wing; aft-fuselage mounted engines, however, require special care to avoid inducing audible structural vibrations. Propulsion noise is treated further in a later section.

Larger aircraft have a thicker boundary layer at any percentile fuselage station, producing a lower-frequency spectrum at corresponding fuselage locations, as illustrated in Fig. 29. Similarly, the sidewall vibration response, which is closely linked to the acoustical transmission, will tend to peak at lower frequencies for larger aircraft, as indicated in Fig. 30. This downward shift of spectral content in noise causes the larger airplane to require a disproportionately high allocation of soundproofing weight, because conventional soundproofing materials perform less efficiently at low frequencies.

IV. Aerodynamics

Scaling

The prediction of aerodynamic characteristics of increasingly larger aircraft has been accompained by steady improvement in analytical and empirical scaling techniques. Most of the effort in aeronautics prior to the Wright Brothers was of a highly experimental nature without theoretical basis, and is characterized by a remark in the 1879 annual report of the Aeronautical Society of Great Britain, "Mathematics up to the present day have been quite useless to us in regard to flying." Even the great experimenter Sir George Cayley (1773–1857), one of the first to separate lift and drag and to recognize the importance of afterbody shape in reducing drag said, "I fear, however, the whole of this subject is of so dark a nature as to be more usefully investigated by experiment than by reasoning."

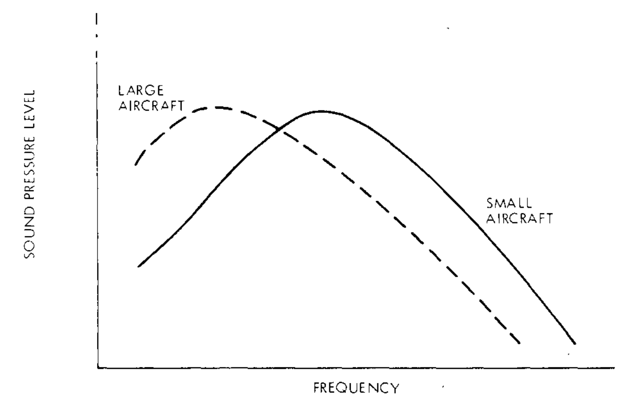


Fig. 29 Frequency distribution of boundary-layer noise (constant flight speed).

The early successful experimenters in the field of aerodynamics eventually found, however, that they could not avoid developing a means to mathematically handle the effects of scale on aerodynamic forces and moments. The lift and drag characteristics of potential aerodynamic configurations were extensively explored by the Wright Brothers in their small-scale wind tunnel. A combination of skill, care, and some fortuitous circumstances avoided the potential Reynolds number problems they could have encountered in scaling up their results by nearly two orders of magnitude between their model size and that of their flight vehicles. A replica of the Wright tunnel with its 22-in.[2] test section is pictured for comparison inside the modern 26- × 30-ft low-speed test section of the Lockheed-Georgia Company V/STOL wind tunnel in Fig. 31.

To arrive at the necessary scaling factor, the Wrights conducted a controlled test in which both a full-scale glider and a geometrically similar wind-tunnel model were constructed. These were tested in flight and in their wind tunnel, respectively; the results were compared in the form of lift/drag ratios as a function of angle of attack. A factor was obtained for correcting model tests to full scale, which could be used for future tests. In essence, they had arrived at the concept of aerodynamic coefficients.

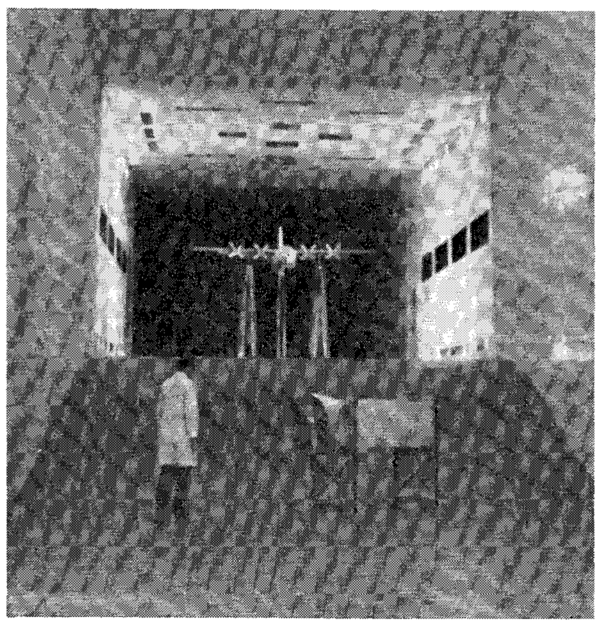


Fig. 31 Wright brothers' wind-tunnel replica inside modern tunnel.

The early basic aerodynamic shapes, such as those with which the Wright Brothers dealt, included very thin wings with very small leading-edge radii; cylindrical wires for structural tension bracing; and interplane compression struts and exposed wooden structure of generally blunt oval or circular cross section. This meant that most of the flow over the vehicle was separated, the flow patterns of both the model and the full-scale vehicle were geometrically similar, and model-scale aerodynamic ratios and coefficients could be accurately applied to much larger-scale vehicles.

The five basic dimensionless quantities which deal with various aspects of the interaction of a fluid flow with objects on or in it are Mach number, Prandtl number, Froude number, Strouhal number, and Reynolds number.

Of these parameters, the first two are not scale dependent at all. The third is scale dependent, but is used in defining the phenomena that occur at the interface of two fluids of primary importance to aircraft. The fourth has some significance in potential resonance between shed vortices and aircraft structural natural frequencies, but the fifth, Reynolds number, is by far the most important of these quantities. To achieve dynamic similarity between model and flight vehicle, the same ratio of inertia and viscosity forces must be maintained so that the Reynolds numbers are the same. The primary significance of Reynolds number is that, for a stipulated Mach number and for given conditions of surface roughness, it establishes the character of the boundary layer.

Drag

The boundary layer dictates, among other things, variations in friction drag, as illustrated in Fig. 32. This plot shows the effect of Reynolds number on skin-friction drag coefficient for a C-5A configuration with differing percentages of laminar boundary-layer flow, the remainder of the flow being turbulent.

The curves show why it was possible about a generation ago to determine full-scale drag coefficients rather simply. A precise scale model of the configuration under development was polished to a very high degree of surface smoothness, was wind-tunnel tested, and the resulting drag coefficients were used uncorrected for scale to predict the full-scale vehicle performance. Though not fully recognized at the time, success in using this technique was due to the fortunate circumstance that the polished model experienced a high degree of laminar boundary-layer flow at its relatively low Reynolds number such that its resulting drag coefficient was very similar to that of the full-scale airplane which experienced essentially no laminar flow at its higher Reynolds numbers.

In general, the percentage of laminar flow on full-scale aircraft is so slight as to be negligible. Thus, the figure

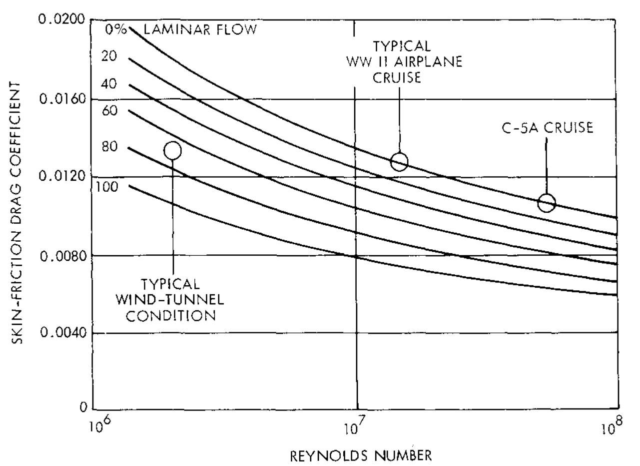


Fig. 32 Effect of Reynolds number on skin-friction drag.

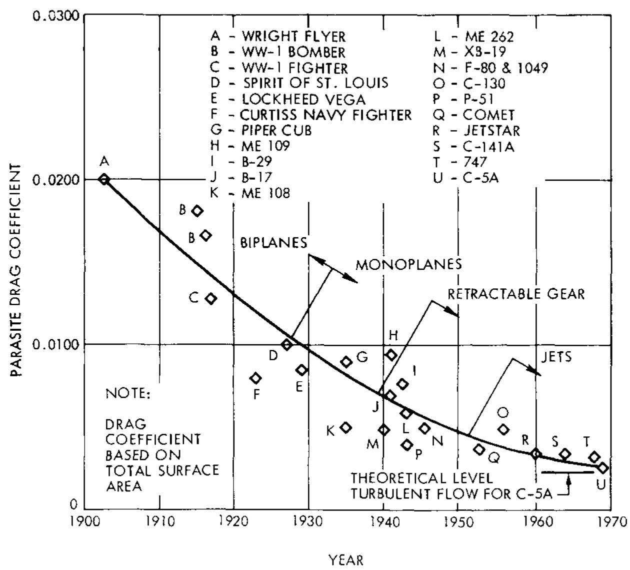


Fig. 33 History of parasite drag coefficient.

illustrates that, as the size of the vehicle increases, the skin-friction drag coefficient continues to decrease.

In the early days of C-5A performance estimation, the possibility was recognized of the existence of a plateau in the curve of skin-friction drag coefficient vs Reynolds number, beyond which increasing Reynolds number would not continue to decrease the drag coefficient. The work of Nikuradse[12] on terminal Reynolds number showed that the Reynolds number at which such a plateau should exist was a function of the average surface-roughness height divided by the local chord length. Computation of the average roughness for the C-141A and the C-5A indicated a value of about 150 μ in. for either, and a resultant drag plateau for each at a Reynolds number more than twice that for best cruise speed for each airplane. This is slightly beyond the Reynolds number range at which definitive flight-drag data exist, and the flight data do not appear to indicate any plateau effect. It may be concluded, therefore, that further increases in aircraft size above that of the C-5A will continue to yield decreases in minimum skin-friction drag coefficient in accordance with Fig. 32, since manufacturing facilities are generally capable of working to given absolute values of tolerances, and the plateau for each airplane will continue to be at about twice the cruise Reynolds number for a given absolute surface roughness.

It is estimated that the C-5A has about seven counts of manufacturing roughness drag; that is due to steps, gaps, and fit. This is about 3% of the total cruise drag. It is probable that this percentage value is inversely proportional to airplane scale. It would appear that an airplane similar to the C-5A, with the same wing loading but twice the takeoff weight, would have a skin-friction drag about six counts less than that of the C-5A, in accordance with Fig. 32, and two counts less for manufacturing roughness. This would yield an improvement in cruise drag of about eight counts, or 3%.

Steady improvement with time has been evident in airplane drag, far beyond scale effects. These advances have contributed substantially to aircraft performance and productivity to help counter the influence of the square/cube law on aircraft structural weight. Figure 33 shows the trend with time of parasite drag coefficient, including interference drag, but not induced or compressibility drag. Modern aircraft are approaching the theoretically best attainable values for skin-friction drag for fully turbulent flow, and further advances of significance will require a change in aerodynamic concept, such as laminar-flow control.

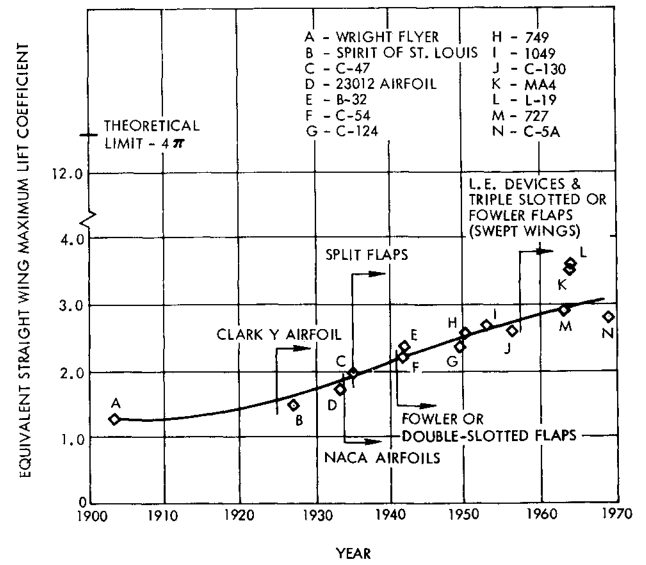


Fig. 34 History of nonaugmented maximum lift coefficient.

Lift

Reynolds number is also a powerful factor in determining the maximum lift coefficient of a wing and its high-lift devices, because of its influence on the tendency of the boundary layer to separate in an adverse pressure gradient. The airfoil section used by the Wrights developed a maximum lift coefficient of about 1.3, which even now is a respectable value for a wing without flaps. Figure 34 shows progress in developing equivalent straight wing, nonpropulsive high-lift systems. The prospects for the future appear bright. Although fairly steady progress has been made, the values to date appear well short of both the theoretical limit and of the values attained by experimental aircraft such as the Mississippi State University L-19 and the Cambridge University MA4 on the figure, which use distributed suction on the wing such that the flow approaches having inviscid characteristics. It is still classified as nonaugmented in nature, since no energy is added to either the flowfield or to the boundary layer.

Shock/Boundary-Layer Interaction

Recent correlation of airfoil pressure data as a function of Reynolds number at Mach numbers above critical has shown that modern transonic airfoils are particularly subject to a large scaling effect because of a shock/boundary-layer interaction process. Even when the proper percentages of laminar

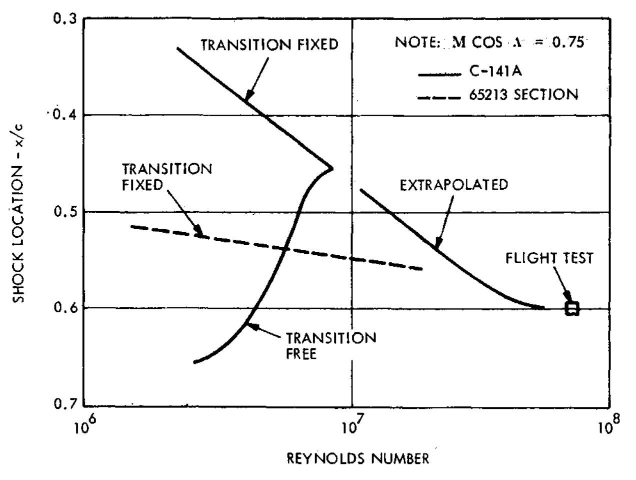


Fig. 35 Effect of Reynolds number on wing shock location.

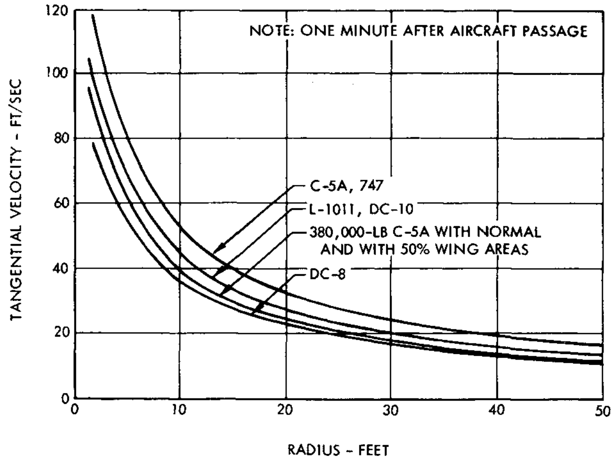


Fig. 36 Tip vortex strength.

and turbulent boundary layer are simulated on a small-scale model at transonic speeds, the formation of a shock wave creates a boundary-layer disturbance with accompanying tendency for trailing-edge separation. These two factors—the strength and location of the shock wave and the extent of boundary-layer separation—interact in a fashion that was only slightly subject to scale effects on the NASA 6-series airfoils of immediate post World War II vintage, but is highly significant on the more recently developed supercritical airfoils.

Figure 35 shows a typical variation of shock location at a given Mach number as a function of Reynolds number for two kinds of airfoils. First clearly observed during C-141A flight testing and subsequently identified on other aircraft, the phenomenon varies greatly in significance with the transonic shape of the pressure distribution on the airfoil upper surface; a flat pressure variation typical of supercritical airfoils is subject to substantially the greatest effect. The figure illustrates that application of airloads data obtained even at Reynolds numbers appropriate for a small aircraft may be quite misleading when applied to a large aircraft without a clear understanding of the interactions involved for the airfoil section used. The aerodynamicists of only ten years ago were fortuitously protected from the consequences of their incomprehension of this shock/boundary-layer interaction phenomenon by the fact that it was then the practice to use a type of airfoil that was insensitive to it.

Vortex Wakes

The advent of the jumbo jets has given rise to considerable concern for the trailing vortex-wake hazard to following aircraft. The extent of this problem has been found to be not directly proportional to airplane size or weight. McCormick, Tangler, and Sherrib[13] developed empirical relationships deduced from flight measurements which appear to correlate well with data from a number of airplanes. Using this computational method, a comparison has been developed of the vortex tangential velocity as a function of distance from the center of its core, for several cases. Figure 36 shows the C-5A at 760,000 lb; at 380,000 lb; and at 380,000 lb with 50% less wing area. The 747, L-1011, DC-10, and DC-8 are also indicated. One minute after the passage of each aircraft, the vortex tangential velocity 25 ft from the center of the core is approximately one-third greater for the heavy weight airplane than it is for two aircraft of half the weight.

The significance of the differences is uncertain in terms of aircraft operations around airports, but surely some increase in separation times behind the larger aircraft will obtain; if large, it could be reasonably important at busy airports. The adversity of the effect is not in question, only its degree.

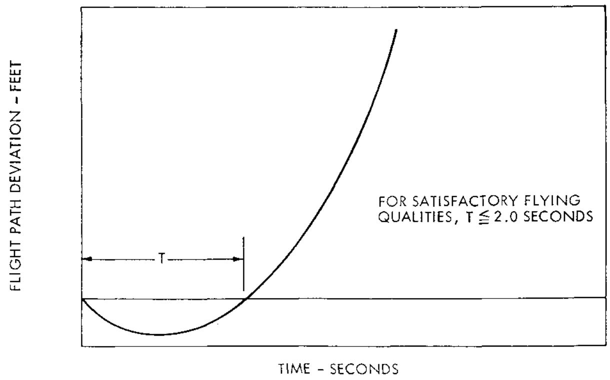


Fig. 37 Typical airplane response to abrupt elevator deflection.

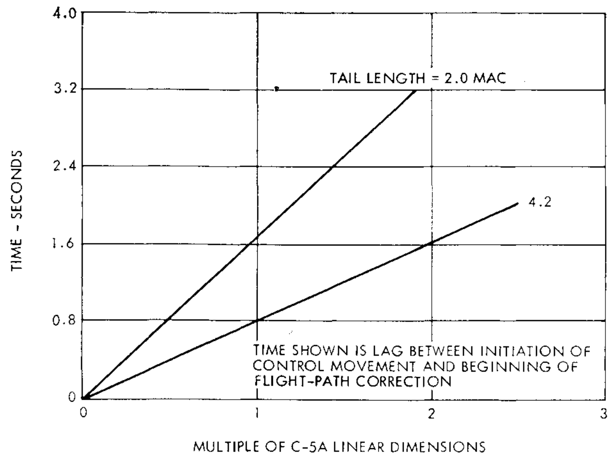


Fig. 38 Effect of vehicle scale on longitudinal response.

Handling Qualities

The flying qualities problem increases with aircraft size even more rapidly than the square/cube law would indicate. Here, a more appropriate relationship would be a cube/fifth-power law stating that the aerodynamic or driving moments which act during aircraft maneuver are proportional to the third power of its dimensions, while the inertial or resisting moments are proportional to the fifth power. The sluggish rudder response of a large boat, compared to a small one at the same speed, is a familiar illustration of this powerful effect.

The Army's flying qualities requirement for its first Wright Flyer was: "This machine must be capable of being flown by a reasonably intelligent man after proper training." Somewhat more sophisticated criteria are exemplified in Fig. 37, developed from research performed at the NASA-Ames Aeronautical Laboratories. These criteria are illustrative of the over-all inertia problem related to aircraft flying qualities.

A flight situation is postulated in which the pilot has just discovered that he is below his chosen glide path during an approach to landing. The initial conventional airplane response to elevator deflection is opposite to that desired, because "up" elevator to decrease sink-rate first applies a net downward acceleration until increasing angle of attack produces the desired upward acceleration. If more than two seconds elapse between first control movement and recovery to original flight-path position, the flying qualities are unsatisfactory. The ability to meet this requirement is obviously influenced by many things, such as control-surface rate of deflection, tail length, lift-curve slope, damping in pitch, and pitch inertia. Obviously, demonstration of satisfactory qualities in a small flying-scale model may be quite irrelevant to the full-scale aircraft, whose pitch response would be much slower.

Interestingly, flying qualities research done for STOL and VTOL aircraft is directly applicable to the determination of appropriate criteria for very large conventional airplanes. In the STOL flight regime, the attainable aerodynamic stabilizing and control moments tend to decrease due to decreasing airspeed, so that the ratio of inertia to aerodynamic moments is increased, just as it is by the increase in inertia moments at constant airspeed due to an increase in vehicle size.

The time lag in pitch response for the C-5A on a typical landing approach is about 0.8 sec. Figure 38 shows the variation of this parameter with airplane scale for a vehicle generally of C-5A configuration. Using the two second criterion, a vehicle approximately 2.4 times as large as the C-5A would exhibit unsatisfactory responses. The C-5A has an unusually great tail length of 4.2 mean aerodynamic chords; if it were only 2.0, as in several smaller aircraft, the critical vehicle size would be less than 1.2 times as large as the C-5A. It seems probable that further increases in airplane size will eventually lead to more applications of some form of direct lift modulation, such as that of the L-1011, or to canard surfaces for glide-path control.

Similar analyses have been made to compare responses to lateral and directional commands. Figure 39 shows that it takes about 6 sec for the C-5A to establish a steady change in yaw angle, compared to about 1.5 sec for a similar aircraft with dimensions half as large. Crosswind approaches are normally made with a combination of bank angle and sideslip to minimize side drift, all of which must be minimized just prior to touchdown by the pilot. At an approach speed of 200 ft/sec, this maneuver can be initiated by the smaller airplane in about $1\frac{1}{2}$ sec, or 300 ft prior to touchdown. The slower response of the larger airplane requires initiation of the maneuver some 6 sec, or 1200 ft, prior to touchdown. Better judgment is required of the pilot to execute this maneuver well; though the C-5A crosswind landing gear feature may not be essential at its size, very much larger aircraft likely will need it.

Control System Design

The handling qualities problems generated by size have a direct impact on primary flight-control system design. The large aerodynamic control surfaces associated with large aircraft result in extremely high surface hinge moments for reasonable deflections. Direct manual control is impractical, in spite of ingenious aerodynamic control-surface balancing. If the pilot has no capability of directly controlling the aerodynamic surface, the requirement for mechanical connection between the pilot's controls and the surface actuation system becomes questionable. In addition, mechanical force trans-

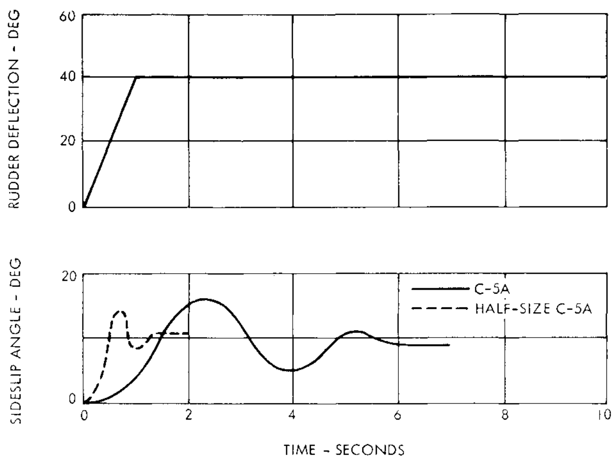


Fig. 39 Effect of vehicle scale on directional response.

mission for very large aircraft results in seriously high control-surface friction and breakout forces. This problem was solved on the C-5A by the use of power control systems and artificial feel, while retaining a direct mechanical connection between the pilot's controls and the control surfaces. The pilot is assisted in overcoming friction forces with a control cable boost system.

Several modern production and experimental aircraft have utilized electrical transmission of pilot commands. Pilot control force is sensed and signals are sent to actuators located near the surface power units which provide deflections proportional to the signal strength. As the reliability of electrical and electronic systems continues to improve, a strong trend has been established in the direction of control entirely through these so-called "fly-by-wire" systems.

V. Propulsion

Thrust Requirements

As aircraft gross weight is increased, the propulsive thrust increase required depends on a number of factors. Direct proportionality between required thrust and gross weight is the most fundamental relationship, but it is applicable only when at least the aircraft mission, lift/drag ratio, and aircraft performance are held constant. This case is illustrated to a degree by a comparison of the C-5A and the C-141A; required thrust was almost doubled while gross weight increased by a factor of 2.3, with some increase in takeoff field length. Historically however, the general trend has been to increase the thrust/gross-weight ratio because of lift/drag reductions (as a result of speed increases, for example); the desire for higher cruise altitudes; and/or more stringent airport performance requirements regardless of, not because of, size growth. This trend is reflected by comparison of the C-5A and the Wright Flyer, where aircraft gross weight grew by a factor of 1000 while useful power increased by a factor of 5000.

Options for Thrust Production

Several options are available for achieving the increased thrust required as aircraft size is increased. Assuming no new technology, two courses are open; the propulsion units of the smaller system may be scaled up, or the smaller propulsion units may be employed in greater numbers. Engine efficiency and specific weight (pounds of engine weight/pound of thrust) are both affected by scaling, as will be discussed subsequently, but no similar changes are inherent when using larger numbers of a given engine; operational considerations tend to weigh against this option, at least for numbers greater than four.

Larger thrust requirements have most often been met, however, with new or modified engine configurations and/or cycles, where the benefits accruing to a continually advancing technology can be incorporated. Also, as the aircraft thrust requirement increases, the number of feasible engine component combinations is increased, and higher energy gas-generator cycles may be employed without encountering minimum practical size limitations.

Scaling Effects on Weight

When an airbreathing engine is scaled to produce more thrust (or power), its specific weight will be increased. If engine cycle characteristics—temperatures, pressures, and velocities—are held constant to maintain the state-of-the-art, the thrust/unit engine airflow is constant. Thus, corresponding flow areas and engine cross sections and, hence, the square of characteristic linear dimensions, are proportional to thrust.

The most simple and direct scaling process implies geometric similarity. With this assumption, a square/cube relationship is established between engine thrust and volume. Further, if the densities of the materials used in construction of the engine are unchanged, the thrust/weight ratio is described by the same square/cube relationship. So, for the simplified direct scaling case, engine specific weight is proportional to its linear dimension, or to the square root of its thrust. This same deterioration of engine specific weight with increasing thrust applies to rotor acceleration and deceleration times; only with a direct proportionality between rotating component weight and engine power would engine responsiveness be unaffected.

In reality, the power plant designer has and uses many opportunities to better the simplified direct scaling relationships. While all characteristic lengths and material thicknesses cannot remain unchanged with increasing engine cross sections, considerable progress in this direction can be made by exploiting aerodynamic, thermodynamic, and structural options implicit in larger size, particularly when dealing with turbine engines. Minimum practical material thicknesses become limiting much less frequently. Hollow blades may be considered for rotating turbomachinery, and/or high aspect-ratio blading may be employed more extensively. Combustor lengths may be held almost constant, and a larger number of stator vanes may be employed, avoiding length increases for aerodynamic similarity in turning and diffusion processes.

The degree of such sophistication which can be applied in scaling a particular turbine engine design determines the ultimate impact on engine weight. Historically, engine specific weight grows with the linear scale factor raised to a power between 0.2 and 0.5, rather than directly with linear scale as would be indicated by application of the square/cube relationship. The tendency toward poorer engine response rates is also reduced as weight growth is retarded; if blade weight grows only with the 2.5 power of linear scale, for example, acceleration and deceleration times, like engine specific weight, will be proportional only to the square root of linear scale.

Engine installation weights generally reflect no penalties with direct scaling. That is, nacelle and ducting weights are proportional to the surface areas involved, while the weights of engine mounts, pylon structures, thrust reversers, and nozzles are approximately proportional to thrust. Thus, with sophisticated engine scaling where length increases more slowly than diameter, nacelle and ducting weights may actually decrease as a percentage of aircraft gross weight.

The weights of many of the engine accessories are proportional to thrust. The weights of some others, such as fuel controls, and sensors, may grow even less rapidly. As a result, engine accessories generally represent a progressively smaller percentage of engine weight as size increases.

Scaling Effects on Efficiency

Specific fuel consumption is improved somewhat as engine size is increased. Specific fuel consumption is inversely proportional to the product of thermal efficiency and propulsive efficiency, where thermal efficiency measures the effectiveness of the conversion from fuel energy to gas horsepower, and propulsive efficiency measures the effectiveness of the conversion from gas horsepower to propulsive thrust.

Thermal efficiency reflects not only the inefficiency associated with the unavailability of heat in the idealized engine cycle, but also includes all real losses invoked in the induction compression, combustion, and expansion of the engine air. In the case of simplified direct scaling, where engine lengths, clearances, and tolerances also scale directly, modest improvements in efficiency will result because the higher Reynolds numbers, which increase directly with linear scale, reduce viscous losses because of the relatively thinner boundary layer. The magnitude of this improvement is size-dependent, however, because of the reducing slope of the friction factor vs Reynolds number curves of Fig. 32. Thus, the benefits derived from scaling up a small engine by a given factor are greater than those for scaling up a large engine by the same factor. When more sophisticated scaling procedures are employed, engine lengths, tolerances, and clearances grow less rapidly or remain constant; blade tip, step and gap losses, leakages, and heat losses become relatively smaller; and thermal efficiency is further improved. While the magnitude of this improvement may be significantly greater than that attributable to Reynolds number, it is still small by comparison with the adverse weight growth. Further, it should be recognized that some thermal efficiency may be intentionally traded in the interest of saving engine weight.

Ideal propulsive efficiency, sometimes called the Froude efficiency, is a function of the ratio of propulsive to free-stream air velocities. As shown in Fig. 40, it increases as the propulsor-imparted velocity ratio, or specific thrust (net thrust/pound of airflow), is decreased. As used here, propulsive efficiency reflects not only ideal efficiency, but includes allowances for propeller/gearbox inefficiency and/or nacelle external drag. The figure also shows typical values of over-all propulsive efficiency for propeller, turbofan, and turbojet aircraft. Propulsive efficiency is generally unchanged by scaling, since characteristic exhaust velocities remain unchanged. The impact of higher Reynolds number on nacelle friction drag and, hence, on propulsive efficiency, is almost too small to recognize, although reductions in friction drag due to reduction in wetted surface area resulting from retardation of proportional length growth may be significant. Reduced radii of curvature associated with shorter length/diameter ratios, however, will tend to increase afterbody pressure-drag coefficients and diminish the gains attributable to reduced wetted surface.

Engine Configuration Considerations

Larger size requirements generally provide the engine designer with more feasible combinations of cycle and geometry that will produce the desired thrust. For example, higher compressor pressure ratios can be used in turbine engine cycles without encountering minimum size limitations and, therefore, higher-energy gas generators and higher bypass-ratio fans can be used effectively to improve over-all cycle efficiencies. When considering a new engine cycle and/or configuration, however, reasonable weight and performance estimates cannot be made using a single over-all engine scale factor; any such design optimization must recognize the complex performance and weight relationships for each component, and the varying dependence of each on the thrust requirement. Total engine weight can then be calculated as the sum of the component weights, and component performance effects can be integrated to reflect their impact on over-all power package performance.

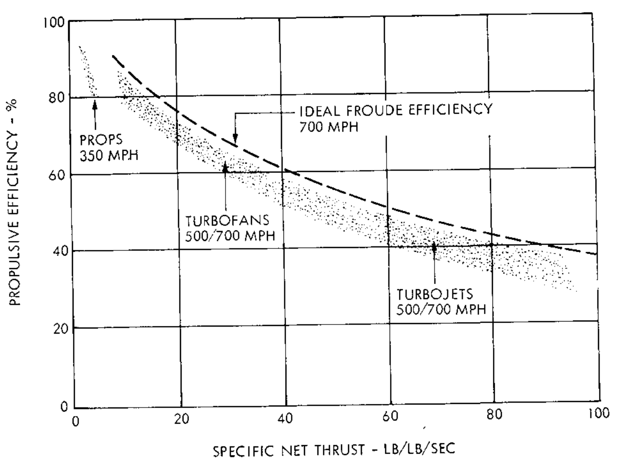


Fig. 40 Effect of specific thrust on propulsive efficiency.

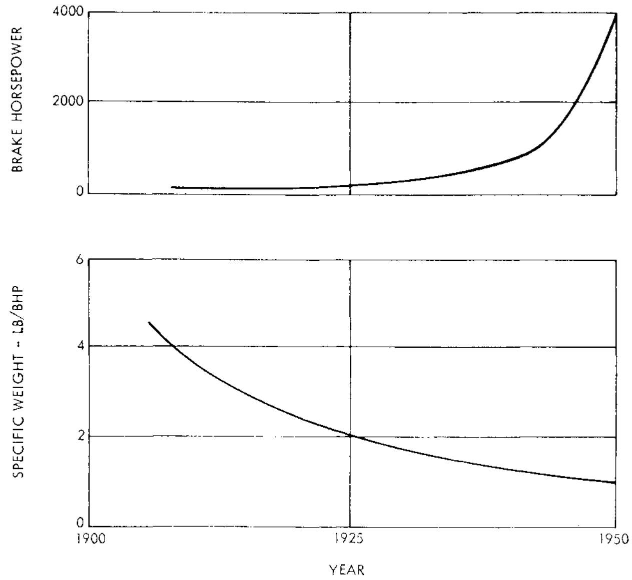


Fig. 41 Trends in piston engine development.

Consider the optimization of turbofan bypass ratio, for example. Even when holding a given gas-generator cycle, the optimum bypass ratio for a given mission requirement will vary somewhat as a function of required thrust. That is, the slopes of the specific weight and propulsive efficiency curves vary with both size and bypass ratio and, therefore, the optimum bypass ratio for a given gas generator depends to some extent on the size of the airplane and the magnitude of required thrust.

Technological Progress

The favorable effects produced by advances in power plant technology have far overshadowed the adverse effects of larger size and more stringent mission requirements. To dramatize this point, consider the advances reflected by a comparison of the power plants used for the Wright Flyer and the C-5A. Although not representative of the best state-of-the-art of its time, the Flyer's engine developed 12 hp, and weighed 151 lb, which represented 20% of the aircraft's takeoff weight; each of the C-5A's TF39 turbofan engines develops 41,100 lb of thrust and weighs 7250 lb. Total C-5A engine weight, then, represents less than 4% of the aircraft's takeoff weight, even though the engine power/aircraft-weight fraction is up by a factor of more than five relative to the Wright Flyer. If the Flyer's engine were scaled to produce TF39 useful power, its specific weight would be more than doubled, even using the most sophisticated engine scaling procedures available. The resulting C-5A engine weight would be almost 1.7 million lb, or about 57 times the current C-5A engine weight. Advancing technology has not only compensated adverse scaling effects, therefore, but has further reduced specific weight to 3.5% of its former value.

The general trends in piston engine development are shown in Fig. 41 for the period from 1903 to about 1950. In the period from 1917 to 1945, the specific weight of the piston engine decreased from three to 1 lb/hp; engine power requirements increased by about 1200%; and the specific power was improved by about 400%. These accomplishments were made possible as a result of improved antidetonation characteristics of fuel, higher rpm and piston speeds, and better breathing through use of larger valves, higher compression, and supercharging. At the same time, the advent of the supercharged engine and greater aircraft speeds widened the range of significant operating conditions to the point that a reasonable compromise between takeoff and cruise performance could no longer be obtained with a fixed-pitch

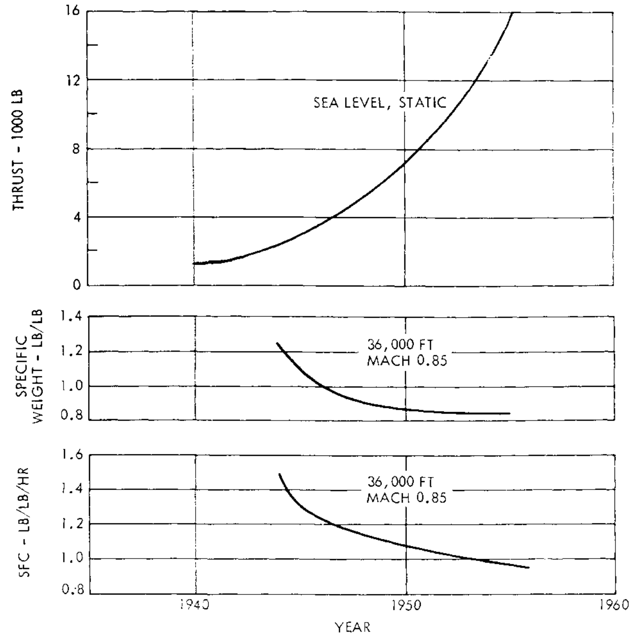


Fig. 42 Trends in turbojet engine development.

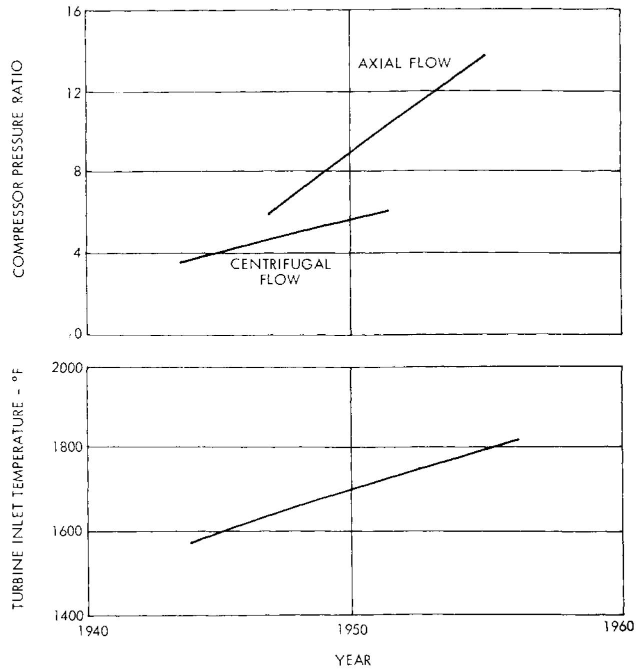


Fig. 44 Turbine engine technology development.

propeller, and the constant-speed, variable-pitch propeller went into production just prior to World War II.

Despite this engine and propeller progress, the demand for higher speeds and altitudes led to the turbojet, weighing only $\frac{1}{4}$ as much as the piston engine and cruising with essentially the same efficiency at 450 mph and with progressively superior efficiency as speed increases. Figure 42 shows the progress in turbojet engine development, which includes the general adoption of the axial compressor in the early 1950's with its lower profile drag and potential for higher pressure ratios. Figure 43 presents the trend of turboprop specific fuel consumption. The efficiency improvements for both turbojets and turboprops are largely attributable to increasing compressor pressure-ratios and higher turbine-inlet temperatures. Trends of these characteristics are shown in Fig. 44. For the most part, uncooled turbine stators and buckets were employed during this period and, therefore, high-temperature materials development was largely responsible for the progress indicated.

Providing more speed than could be achieved efficiently with a propeller, and better propulsive efficiency than the

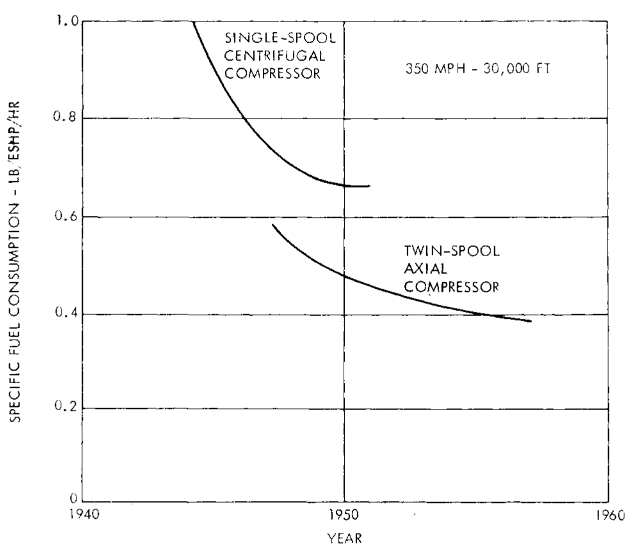


Fig. 43 Turboprop specific fuel consumption.

turbojet, the turbofan engine extended turbojet technology. The increased thrust available provided improved takeoff performance and reduced cruise specific fuel consumption, but was accompanied, initially, by small increases in engine specific weight. The drive for improved efficiencies at cruise has continued through the past decade and the results are compiled in Fig. 45. The current generation of turbofans, represented by the TF39, reflects a significant advance in performance over the previous generation, represented by the TF33. In one step, twice the thrust has been provided while reducing both specific weight and specific fuel consumption by about 25%. The impact of these improvements can be characterized by considering the use of a scaled TF33, rather than the TF39, for the C-5A; to meet the same mission requirements, the aircraft gross weight would almost double.

Such advances reflect much more than improved propulsive efficiency from higher bypass ratio. Thermal efficiencies have been improved through increases in pressure ratio from 15 to 25, while turbine-inlet temperature increases from 1800°F to 2400°F have provided increased specific power output and, therefore, decreased gas-generator specific weight. Thus, the weight benefits accruing to the smaller, higher-energy gas generators have more than compensated the adverse scaling effects related to the larger fans. These improvements are founded on advances in air-cooled turbine technology, compressor-stage loading, and high-pressure compressor matching techniques using either twin spools and variable-geometry compressors or triple spools.

Good and rather detailed presentations of the history of aircraft engine development have been made by A. G. Newton,[14] E. S. Moult,[15] and S. G. Hooker,[16] the latter in the 58th Wilbur and Orville Wright Memorial Lecture.

Other Considerations

Nonperformance considerations frequently have a major impact on engine selection, performance, and weight, and often are affected significantly by engine size. Cost, noise, engine wakes, and foreign object ingestion are noteworthy examples. Engine cost/pound of thrust generally decreases as thrust is increased, assuming production of a fixed number of units. Typically, however, fewer numbers of large engines are required, and the failure to move far down the production learning curve can easily diminish or reverse cost advantages.

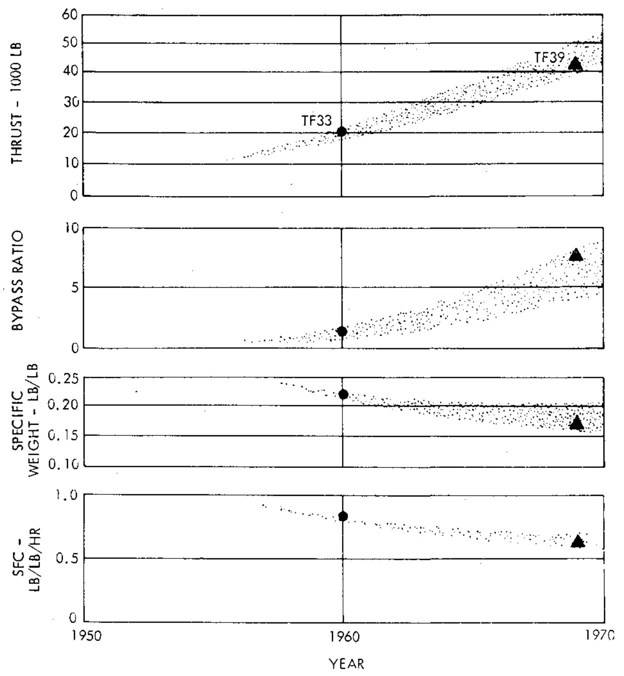


Fig. 45 Trends in turbofan engine development.

The acoustical output of the propulsion system, normally predominant at takeoff, has followed a general trend of steady increase with vehicle size. There have been significant variations from the mean trend, due to the temporal effects of power plant evolution. For example, early small piston engines produced rather low-level line, or discrete frequency, spectra of the type shown in Fig. 46. As turbojets arrived, the typical spectrum became a random one resulting from shear forces acting in the jet efflux, as illustrated in the figure. More recently, the turbofan—acoustically a shrouded propeller—has reversed the trend toward higher-intensity jet noise, but it has increased the discrete-frequency portion of the spectrum at higher frequencies, because of the fan whine.

In general, the turbojets have produced the most noise. The large turbofans have much lower jet noise emission, but more high-frequency fan noise. Jet noise also propagates further since midfrequency noise is not absorbed by the atmosphere as readily as is high-frequency noise. Consequently, a turbofan may have higher and more irritating noise levels very near the aircraft, but at some distance away the noise is lower. The over-all result is that large turbofan aircraft are considerably quieter than they would have been if powered by turbojets of equal thrust. Thrust has been about doubled while noise has remained roughly unchanged. Turbofan noise is also more readily attenuated by noise-suppression devices in the nacelle.

The combined fan and turbine exhaust wakes from progressively larger engines are causing concern in terms of damage to ground installations and equipment. The total energy from a turbofan expelling upwards of 1500 lb of air/sec is formidable; both aircraft ground operations and physical articles exposed to the wakes must be designed to cope with the problem.

Assuming a given inlet Mach number, the susceptibility of the engine to foreign object ingestion can be related to ground clearance, defined nondimensionally by the height of the intake centerline above the ground divided by the intake throat diameter. Figure 47 illustrates, for a given thrust at liftoff, the reduction in ground clearance accompanying an increase in bypass ratio from 0 to 8. One fundamental advantage of high-wing configurations is clear.

The Wright Brothers, interestingly, had what is probably the world's first aeronautical foreign object ingestion problem in an air intake system of their 1902 glider! Octave Chanute[17] describing a landing, concludes " . . . motion being nearly stopped, the apparatus lands squarely and the man, still prone, inhales a little sand, only a few grains. . ."

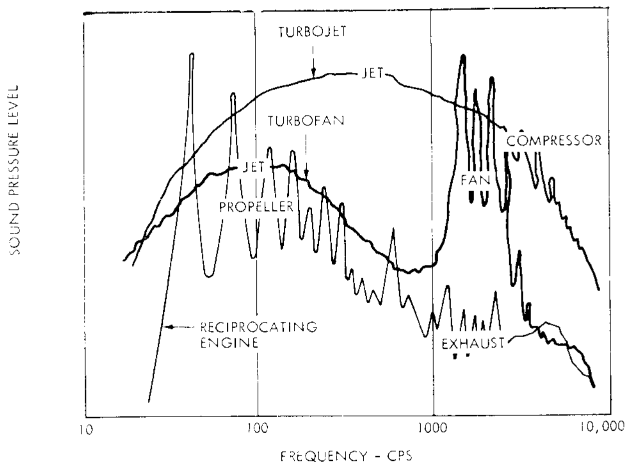


Fig. 46 Typical propulsion noise spectra.

VI. Systemics

The relationship between the required capability or capacity of the various functional systems on an aircraft and the size of the aircraft generally cannot be derived accurately by simple projections. Some insight can be gained, however, by plotting capacity trends and evaluating rationales for deviations. These factors, plus the effect of technological developments on weight in a number of system areas, can be analyzed to show how systemic limitations on aircraft growth have been avoided. In this general area, it seems more orderly to discuss all requirements before addressing any accomplishments, and this practice is adopted for this section.

Power Actuation Requirements

The relation between the capacity of the power-actuation system and aircraft size is complex and varies substantially with the type of actuation system and with the aircraft mission. The operating times for systems such as the landing gear or flaps are generally not affected by aircraft size. The actuation system power increases proportionally to the actuation forces, which are roughly proportional to aircraft weight. As discussed in the aerodynamics section, however, primary flight-control surfaces are required to achieve a maneuver capability virtually independent of size. To accomplish the same angular displacement of the aircraft in a given time, the areas of flight-control surfaces and the hinge moments must increase while the rates of surface movement remain as high, or even increase. As a result, the power required by the flight-control systems increases substantially with aircraft size.

As illustrated in Fig. 48, hydraulic horsepower requirements increase in a pattern vaguely related to weight ratio to the

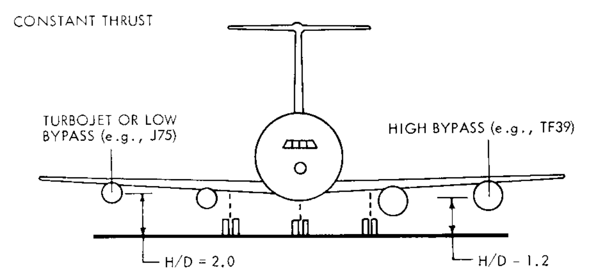


Fig. 47 Engine inlet ground-clearance effect of bypass ratio.

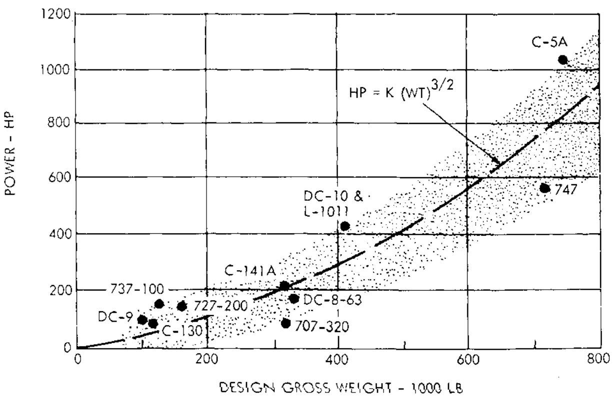


Fig. 48 Hydraulic power required.

$\frac{3}{2}$ power. This increase results from both the higher power requirements for specific functions just noted, plus added applications typical on larger aircraft. When hydraulic power is chosen for primary controllability, multiple hydraulic power sources are required, and hydraulic transmission lengths increase with aircraft dimensions. The aircraft mission also affects the required hydraulic horsepower, accounting for a significant part of the spread of values shown in the figure. Bomber or air-drop aircraft, which are required to open doors in flight, or aircraft which deploy or retrieve devices while airborne, usually require additional hydraulic system capacity.

The weight of mechanical power transmission, such as torque-tube drives from a central gearbox to the flap actuators, increases at a rate which is more than proportional to transmission path length because of the higher power required by the larger aerodynamic surfaces. Because of the great latitude available in designing such systems, no simple assessment of scale effect is possible. Mechanical system weights have historically been proportional to gross weight to the 1.0–1.3 power.

Because there are very few electrical actuation systems, the electrical power requirements are influenced by a number of factors in addition to aircraft weight, as shown in Fig. 49. High among these is the substantial power consumption of galleys on commercial passenger aircraft. The power requirements for instruments, communication, and navigation equipment are not directly size-related. However, as aircraft size, cost, and the penalties for not completing the mission increase, the number of different and/or redundant items increases, thus increasing the required electrical power. Internal lighting and control requirements, the length of the electrical transmission lines, and the use of multiple electrical power sources for reliability all increase with the aircraft size.

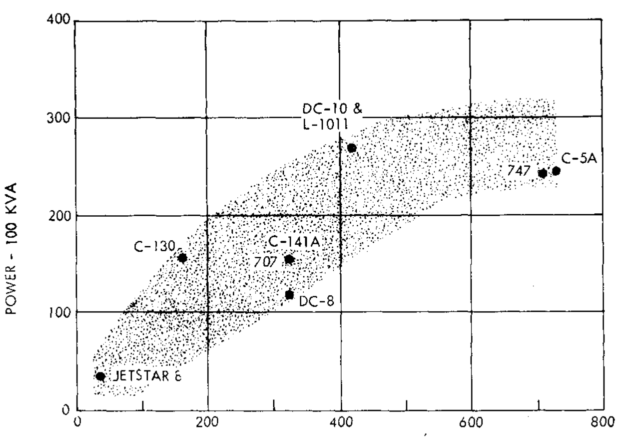


Fig. 49 Electrical power required.

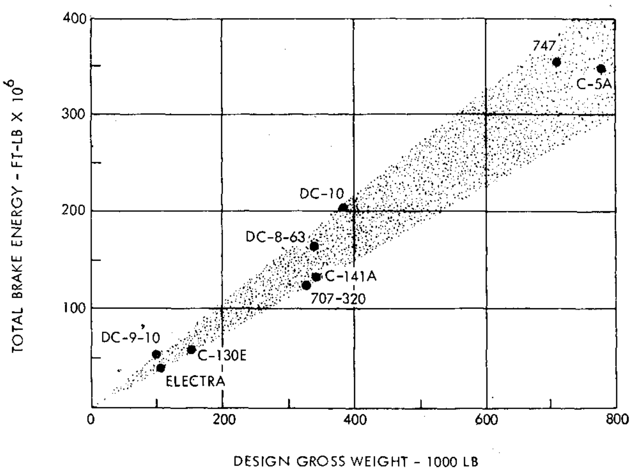


Fig. 50 Brake heat-sink required.

Deceleration Requirements

The necessity of stopping an aircraft on the runway, either after landing or for a rejected takeoff, introduces a number of substantial aircraft design considerations. The energy which must be dissipated by some means is nearly proportional to the aircraft weight and to the square of the velocity at the time the deceleration is initiated. A variety of aircraft systems has been used to provide deceleration, including wheel brakes, thrust reversers, and drag devices, as well as those used primarily on military aircraft, including drag parachutes and gound-installed arresting systems.

Takeoff and landing roll requirenents are usually consistent with current runway lengths, although gradual pressure for larger fields has caused them to creep up with time. This forces large aircraft to achieve takeoff and landing speeds which are somewhat independent of design gross weight, at least between two successive generations. Velocity, therefore, becomes more of a secondary variable in the energy equation, and energy dissipation requirements are nearly proportional to the aircraft weight, as borne out in Fig. 50.

Landing Gear Requirements

The landing gear on aircraft have changed substantially from the fixed, small-wheel arrangements usual before World War II. As paved runways and taxiways became more common, the compatibility between the aircraft's flotation characteristics and the airport's flotation capability rose in importance.

In order to achieve satisfactory flotation, tire footprint should increase with aircraft weight. Tire-size increase serves until multiple-wheel bogies are necessary, and eventually multiple bogies are utilized because the equivalent single tire size cannot be stowed within an acceptable aircraft contour. The smaller tires are heavier/pound supported; therefore, flotation capacity increases more slowly/pound of added gear weight. Weight savings could accrue by decreasing aircraft flotation capabilities if runway strengths were increased; however, an additional constraint would soon be confronted since the volume within the wheels available for brake energy-absorption material would not be adequate for the energy-dissipation requirements.

As aircraft dimensions increase it is necessary to have longer main landing gear struts to preclude contact of the aft fuselage with the runway during takeoff rotation. The resulting increased height of the fuselage above the ground increases the weight of the landing gear, integral stairs, escape systems, ramps, and various ground interface systems. One of the operational requirements for the C-5A was that the cargo floor be adjustable to truck-bed height, resulting in the incorporation of a kneeling capability in the landing

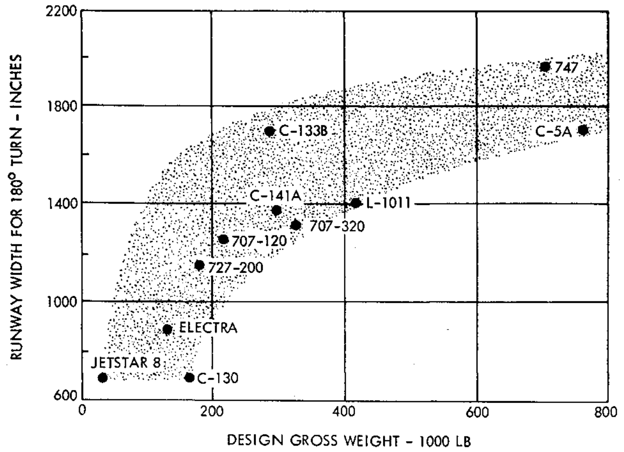


Fig. 51 Aircraft turning capability for 60° NLG angle.

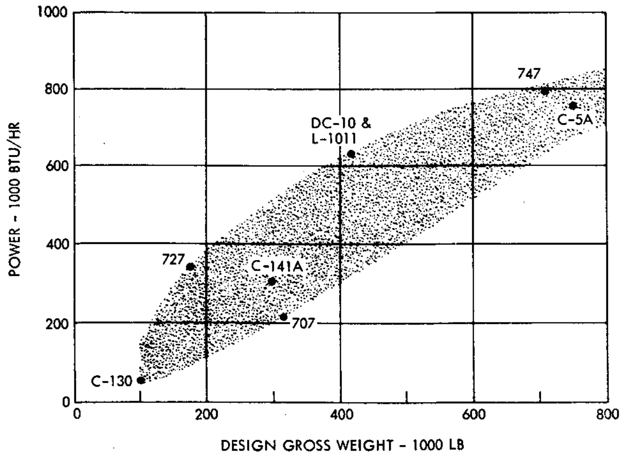


Fig. 52 Air conditioning requirement.

gears. The weight of this capability was offset by the concomitant weight reduction of the integral ramps from the cargo floor to the ground.

In addition to runway and taxiway strength, the widths of these surfaces have a marked effect on landing gear design as aircraft size increases. As shown in Fig. 51, the turning width of aircraft has increased substantially with gross weight; existing pavements, however, are beginning to exert a constraining influence. In order to achieve the turning performance shown in the figure, the large aircraft have had to resort to either steering or castering of part or all of the main gear bogies.

Pressurization and Air Conditioning Requirements

Pressurization and associated temperature control were required as it became more efficient for aircraft to fly at higher altitudes. The capabilities of these systems are related to aircraft size and to the degree of dependency on ground power units. The capacity of the air conditioning equipment is roughly proportional to the cabin dissipating area and, therefore, increases at a rate less than proportional to aircraft weight, as shown in Fig. 52. Interestingly, the air conditioning requirements on supersonic transports will introduce a dramatic step change in the air conditioning requirements when, for the first time, the airplane will cruise in air warmer than can be introduced directly to the cabin.

Systems Technology

Advancements in the design of systems have increased capacity/pound of system weight, assisting in offsetting the effects of the square/cube law. As with structural and aerodynamic analyses, the availability of high-speed computers has significantly changed the analytical approach to the design of aircraft systems from one of approximating a large number of system design parameters and limiting the number of design iterations, to one of accurate mathematical modeling, very complete iteration, and much more precise solutions which allow system designs to be more nearly optimum.

The computer capability now available also permits meaningful flight simulation to be conducted even before the configuration of the aircraft is finalized. Concurrent development of the concepts of the augmentation systems and control-surface areas, for example, can result in substantial savings in structural and system weights while ensuring the attainment of the required handling qualities. Development of the C-5A stability augmentation systems while concurrently sizing the stabilizers and control surfaces resulted in weight savings of hundreds of pounds.

Advancement in hydraulics system technology is shown in Fig. 53. The rate of technology improvement has been impressive, but it is doubtful that more than a fraction of it can be maintained. The effect of recent hydraulics technology advancements on the C-5A is illustrated by the fact that the actual hydraulics system weight of approximately 7000 lb would have been in excess of 23,000 lb had the technology existing 15 years earlier been used. The reduction in weight derives partly from improvements in components such as pumps and valves, but the major saving is in the selection of material and design of the distribution lines. High-strength tubing material such as AM350 steel, permanently welded fittings, increased flow velocities, and extensive use of manifold valves have substantially reduced system specific weight.

Technology advancements in electrical power-generating equipment have also been commendable, as shown in Fig. 54. For example, the weight of the Boeing 747 electrical power-generating equipment is less than half of what it would have been had the technology existing 15 years earlier been used. The primary design advancements leading to this improvement in the 747 are the use of higher generator speeds and higher permeability magnetic materials. Other contributors include the use of high-voltage AC in lieu of 28-v DC; solid-state controls; and higher-strength copper alloys with improved insulation for wiring. The significant improvement noted in the figure for the L-1011 system results from the use of oil-spray cooling of the generator windings and the integration of the generator with the constant-speed drive.

Utilization of electronic systems has increased with aircraft size to meet the demands of increased utilization and reliability for these very expensive aircraft. Onboard maintenance analysis equipment becomes highly desirable for minimizing maintenance down time. The size of the aircraft,

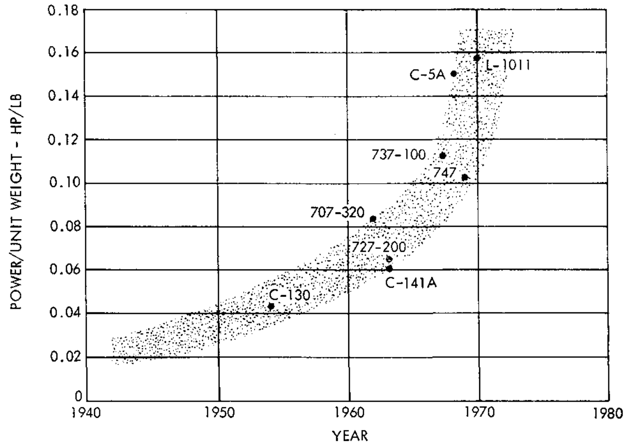


Fig. 53 Hydraulic system technology.

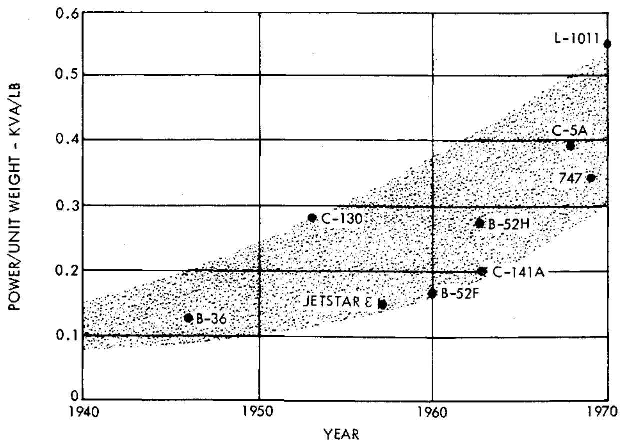


Fig. 54 Electrical generating equipment technology.

in terms of the number of passengers or amount of cargo carried, has an effect on the costs of landing diversion, making it profitable to increase the reliability of automatic landing systems by increased redundancy. These considerations, together with a similar rationale for communication and navigation equipment, result in a substantial increase in the amount of electronic capability in larger aircraft. Advances in the use of integrated and microminiaturized circuits have resulted in individual elements of electronic equipment being reduced in size and weight. The net result is an increase in the total weight of an aircraft complement, but a generally decreasing percentage of the aircraft gross weight. The variation in requirements, and therefore in data, for these systems is so great as to make a graphic presentation meaningless.

Improvement in brake technology has recently been achieved by a significant departure from previous designs. The major weight in a brake is the heat-sink material; the energy absorption/pound of braking material on a number of aircraft is shown in Fig. 55. Prior to the mid-1950's, organic-lined steel disk brakes were used. From the mid-1950's to the mid-1960's, metallic linings and multiple steel disks were used, and are used on most current aircraft. As indicated, the beryllium disks on the C-5A result in a 50% reduction in the weight of the heat-sink material relative to comparable steel brakes.

There has been a continuous improvement in the efficiency of air conditioning equipment, as shown in Fig. 56. This improvement is influenced by the availability of sufficient bleed air from gas-turbine engines to operate air-cycle refrigeration units. The strongest influence, however, is more efficient air-to-air heat exchangers utilizing extremely thin

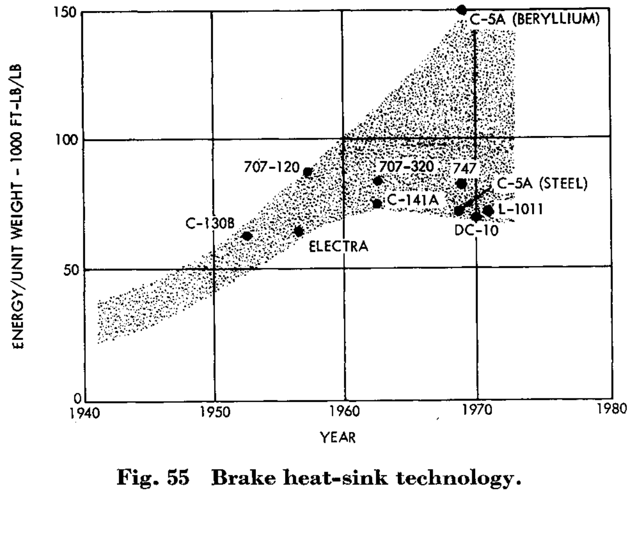


Fig. 55 Brake heat-sink technology.

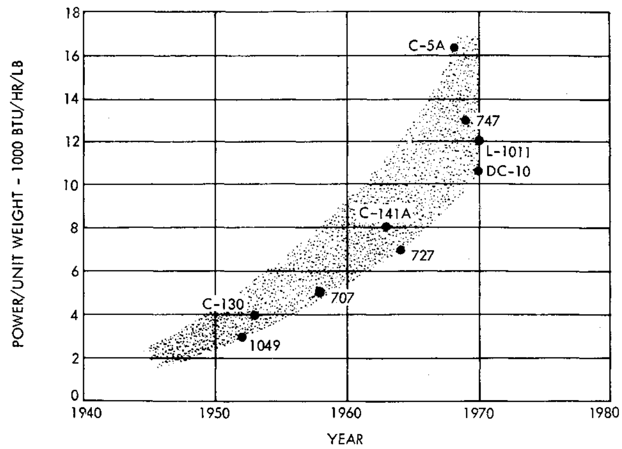


Fig. 56 Air conditioning technology.

fins and irregular flow surfaces to increase turbulence, and the use of improved high-temperaure materials. The weight of the air conditioning equipment in a modern aircraft is much less than 50% of what it would have been had 15 year old technology been used.

VII. Manufacturing and Testing

Many of the broad and size-independent technological advances discussed, coupled with the facility implications of aircraft size alone, have imposed challenging requirements on manufacturing and test facilities, equipment, and personnel. Although conceptual designs can always be visualized beyond a current state-of-the-art for manufacturing, substantial constraints often apply to the practical application of a new or modified design philosophy. Even when cost/benefit ratios support some new design approach, manufacturing does not always have sufficient calendar time to respond to it. Some good work is being done in developing concurrent advancement programs to reduce the problem, and there is room for more.

Constraints on Design

Major sculptured components of modern aircraft can be extremely efficient structures by the elimination of joints, attachment points, and complex subassemblies. Forgings, for example, which have played a vital role in the development of aircraft, originally were confined entirely to the engines. With the adoption of aluminum and magnesium alloys during the 1920's forging was extended to small structural attachment fittngs.

As aircraft size grew, larger forgings were sought for major structural components. Press capability grew slowly from 10 tons in the early 1900's through the 18,000-ton closed-die forging press during World War II, to the United States Air Force Heavy Press Program of the early 1950's with two 35,000-ton and two 50,000-ton presses, still the largest available today. The forgings for the C-5A main and side frames, the latter shown in Fig. 57, were restricted in size and definition by the 50,000-ton press capabilities. With greater press capacity, these forgings could be larger, with attendant weight savings; subsequent machining could be reduced by better detail definition; and higher mechanical properties would result from improved grain-flow orientation.

Fortunately, metal-removal technology has kept pace with requirements. Figure 58 illustrates the availability of profile milling machines capable of handling large aircraft components.

Limitations on aluminum sheet size result in additional joints, each of which adds significant weight to the structure. Occasionally these inefficiencies completely eliminate candi-

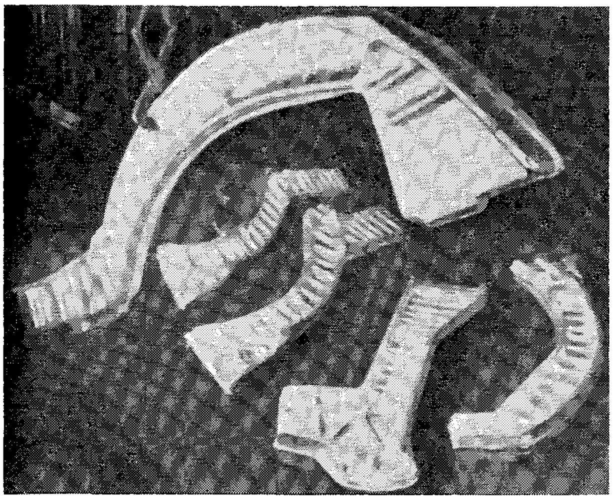


Fig. 57 C-5A sideframe forgings.

date materials. The original C-5A cargo floor surface, which is subjected to significant wear, abuse, and corrosive spillage, was to be fabricated from titanium face sheets because of a superior wearing surface and of weight efficiencies over the most competitive aluminum structure. But the 12- × 3-ft largest available titanium sheets, compared to an optimum size in excess of 40 × 4 ft, reversed the weight advantage and caused the rejection of titanium. Similar examples are found at any point in time in extruded products of virtually all materials.

Major changes in manufacturing operations for large aircraft have been initiated to remove design constraints. Typical are the use of bonded assemblies and of chemical milling to sculpture parts for minimum weight. Though there are only about three times as many parts in the C-5A as there are in the C-141A, Fig. 59 shows that there are more than 15 times the number of bonded assemblies. Chemical milling on the C-141A involved only about 1100 parts, a maximum of three cuts, and a 20-ft tank for a maximum part size of 25 lb. Many of the 5700 C-5A chemically-milled parts require ten cuts and tanks up to 48-ft deep; the largest part weighs over 850 lb before milling. The impact of such changes on production manpower, training, and facilities is substantial, requiring special facilities and a large expansion and retraining of a skilled work force.

Human Factors

The equipment and computer technology associated with numerically controlled machining is sufficiently advanced to produce the most difficult configurations. Limitations are found, however, in the availability of suitably trained technicians to translate from the drawings to machine language.

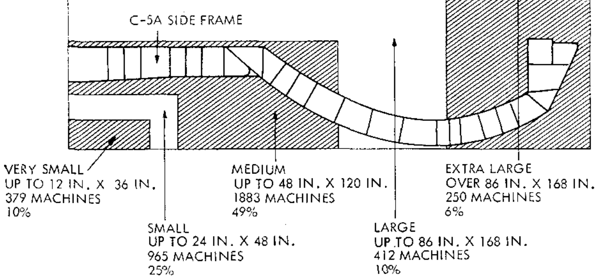


Fig. 58 Available aerospace profile milling machines.

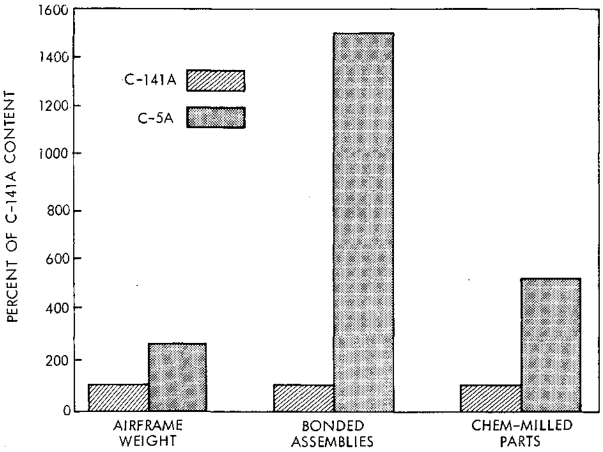


Fig. 59 Fabrication trends.

Although automation has been satisfactorily applied to automatic fastener installation equipment for many years, the facilities have been limited primarily to two-axis operations with a small number of changes in pitch and fastener size. Structural efficiency demands constantly variable pitches, random fastener patterns, variable fastener sizes, and three-axis installation while maintaining the precision hole tolerances required of modern fasteners. In the case of the C-5A, the design requirements for this equipment are so complex that the majority of the fastening is accomplished by conventional manual operations.

While the size and ability of aircraft have been increasing over the years, these same characteristics of the men who build them have remained relatively constant. Accessibility of stock becomes a significant factor in manpower utilization. Many jigs are two and three stories high, and final assembly areas require that even greater heights be climbed to reach work stations, as indicated in Fig. 60. Stock required must be made readily available at these locations and heights. A round trip between the fourth floor and the water fountain also can be expensive. Additional problems are created by large, heavy assemblies. Sections of smaller aircraft which formerly could be moved into position by hand now often require overhead cranes and other devices such as air-pad supports.

Test Facilities and Instrumentation

Increase in aircraft size has created rather spectacular requirements for buildings to house testing operations. On the other hand, test equipment requirements have grown

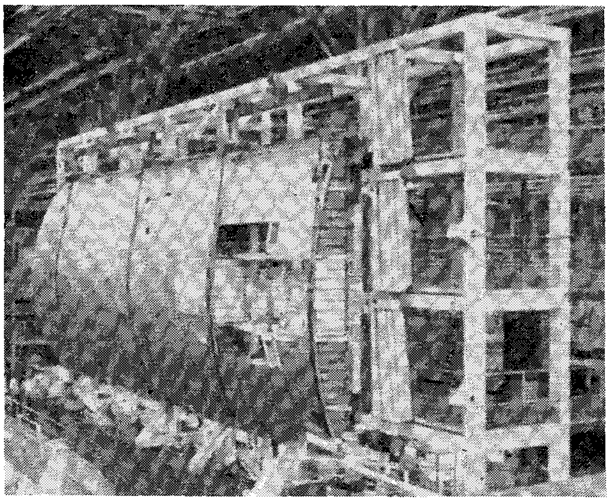


Fig. 60 Multilevel assembly fixtures.

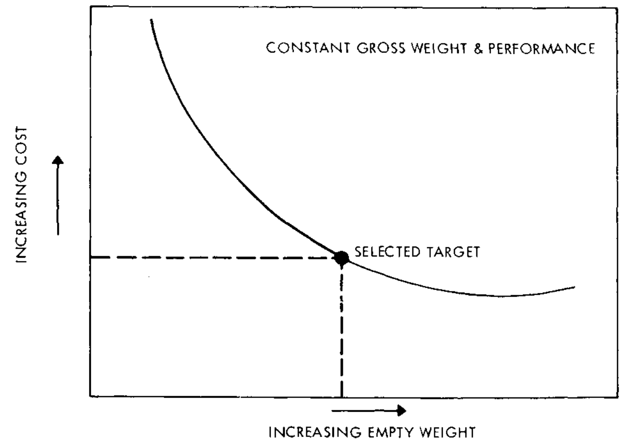


Fig. 61 Cost of weight reduction.

slowly—about proportional to gross weight. The number of strain gages and deflection gages required in static and fatigue testing is almost a linear function of the surface area. Scale factors on flutter models create mass-to-stiffness correlation problems which are difficult to resolve with current model materials. But neither test facilities nor instrumentation can be classed as major design constraints, and it is unlikely that they will ever constitute a significant limitation on size growth.

VIII. Costs

General

The basic driving force toward larger airplanes has been the desire for lower total costs associated with moving goods and people, and for the ability to move them further. In the specific case of commercial operations, the criterion is profit or actually, return on investment, but cost is an adequate element of either for current purposes. Additionally, in the case of cargo aircraft, dimensions and payloads have increased to permit carrying larger single units, such as containers, bulky military equipment, and automobiles. The effect on operating costs and revenue of size increase is a complex subject which historically has been so intermingled with the cost effects of changing such things as speed, comfort level, construction techniques, and technology that it is difficult to identify separately. Nevertheless, certain generalized qualitative and semiquantitative conclusions can be derived from the historical data. The following discussion is based primarily on cost trends of commercial aircraft, since consistent and statistically significant data are available.

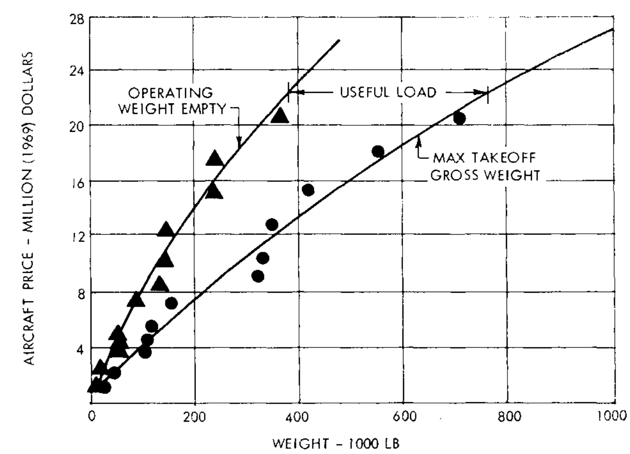


Fig. 62 Effect of gross weight on price.

Such data are not available for military aircraft, but the same trends probably hold true.

The total cost of moving goods and people rightfully includes all costs from origin to destination, including the surface elements at both ends. Traditionally, costs associated with moving the cargo (or passenger) from the time it is on board the aircraft until it is ready to depart from the aircraft are termed "Direct Operating Cost" (DOC). They are highly sensitive to aircraft price, aircraft characteristics, and distance flow.

Those costs associated with aircraft terminal operations, sales, administration, and cargo or passenger movement between the aircraft and the surface systems are called "Indirect Operating Cost" (IOC). They are not generally functions of the distance flown, yet are ultimately a cost to the airline allocated on the basis of units moved, both aircraft and cargo. Costs on surface systems beyond the terminal are generally not allocated to the airlines and are not included in IOC.

Development and Production Cost

As mentioned earlier, different levels of technology application in design and fabrication result in different useful-load fractions. At any point in time, and for a specific set of requirements, the most cost-effective level of technological sophistication is seldom the limit of the state-of-the-art, i.e., the maximum possible level of knowledge or capability. Indeed, although very difficult to quantify, it is obvious that a relationship like that of Fig. 61 exists between empty weight and manufacturing cost for a fixed payload or gross weight. For customary and reasonable empty weight fractions it is always possible to reduce empty weight at increased manufacturing cost, or it is possible to reduce manufacturing cost by increasing empty weight, within limits.

The C-5A is a case in point. The C-5A contract specified well-related requirements for cruise speed, payload, range, takeoff and landing distances, rate-of-climb, initial cruise altitude, and a multitude of physical parameters and other mission capabilities. In addition, it specified a maximum empty weight. Many costly weight-saving features had to be incorporated in order to meet that weight. For example, as discussed earlier, beryllium was incorporated in the C-5A brakes in order to save 3050 lb/aircraft at a cost over \$100/lb saved/aircraft. Other weight-saving techniques were identified at even higher costs/lb saved; fortunately it was not necessary to incorporate all of them to meet the contract weight.

The quantification of a curve such as that in the figure for a specific program is virtually impossible, since it must recognize not only the simple evaluations of the effect of each alternate weight-saving change on a sterile basis (assuming all the rest of the program is unaffected) but must also account for all the interactions of all possible changes, both in the context of their direct physical interfaces and in terms of

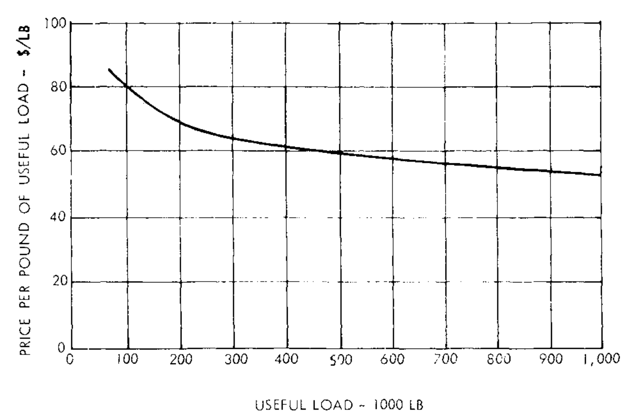


Fig. 63 Price variation with useful load.

the subtle and essentially indeterminant reverberations and cascade effects throughout the entire development and manufacturing process of schedule delays and resequencing. All this is compounded by the added variable that the total cost effect of saving each pound is also a function of the time at which the incorporation decision is made, both in calendar and in chronological relation with all other changes implemented. It is apparent that the uncertainty of such a curve exists, not only at all points away from the target weight and cost, but also at that special point, since the exact composition of design decisions to meet target weight cannot be known at the time of original design and cost estimates.

In spite of all these complexities of quantification, it is not difficult to visualize a saving of hundreds of millions of dollars on the C-5A program if freedom had existed to increase the empty weight in the specification by, say, 5% (about 16,000 lb). Even then, virtually all of the many specification items could still have been met, and the savings would probably have made it cost effective to violate slightly the remaining few.

Very roughly, the same level of design and manufacturing sophistication appears to be optimal for all aircraft of a given era and intended use. Figure 62 is a plot of the unit price of 1960–1970, turbofan-powered, passenger aircraft as a function of maximum gross weight and of operating weight empty. An attempt has been made to adjust these prices to 1969 dollars and to a common break-even production quantity of 200 aircraft, but lack of specific learning curves and other pricing data for the various manufacturers prevents high accuracy in this adjustment. Nonetheless, the curves are considered a reasonable indication of the effect of size on price at a nearly constant state-of-the-art.

The curves of Fig. 62 permit construction of that on Fig. 63, which shows that the price/pound of useful load decreases as size increases. This indicates that the reduction in price/pound of gross weight as size grows more than offsets any square/cube law reduction in useful-load fraction.

Direct Operating Cost (DOC)

Direct operating costs include the cost to fly, insure, and maintain the airplane, plus amortization of the original purchase price over its anticipated useful life. Two principal factors have combined to produce dramatic reductions in DOC over the years: 1) the technological and manufacturing advances discussed previously and 2) increasing size, per se, at a given state-of-the-art. Other factors—increasing convenience (speed and comfort), and regulatory requirements—have acted to inhibit this decrease. Figure 64 indicates the effect of increasing gross weight and payload at (very approximately) constant state-of-the-art. All aircraft plotted, except the DC-7 and 1049G, are 1960–1970

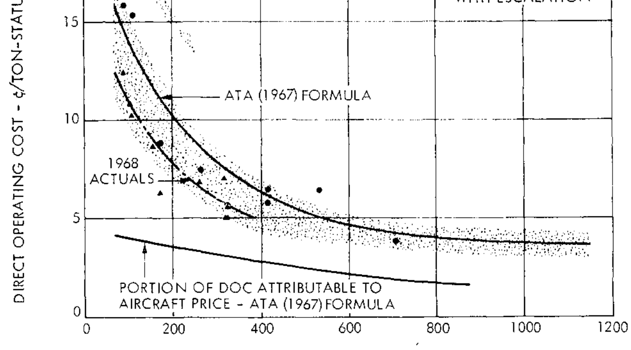


Fig. 64 Effect of weight on DOC.

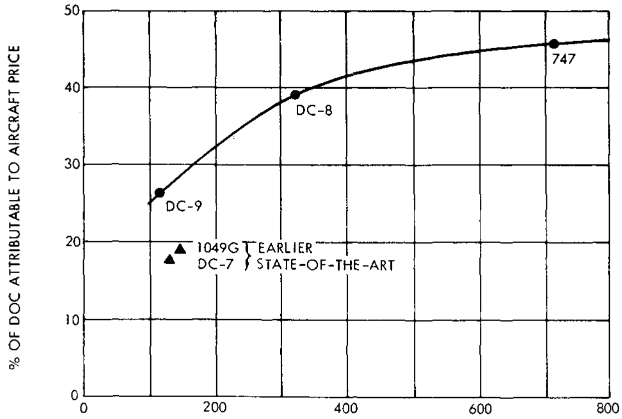


Fig. 65 Effect of weight on price portion of DOC.

turbofan-powered passenger aircraft. The center curve is based on operating costs reported by airlines to the Civil Aeronautics Board in 1968, and includes ten aircraft, from the 78,000-lb BAC 111-200 through the 328,000 lb Boeing 707-302B. For purposes of consistent extrapolation to higher gross weights, the upper curve is fitted through data points computed by the 1967 ATA DOC equation for these same aircraft plus the L-1011, DC-10, and 747. The DC-7 and 1049G points also are computed to the ATA ground rules, with proper escalation, and, being aircraft of the previous generation, illustrate the effect of technology improvements.

The most significant factor to be observed from these gross data is the marked flattening of DOC at gross weights above 750,000 lb for airplanes of the 1960–1970 average state-of-the-art. Before drawing any conclusions, the components of DOC and IOC, and the premises of the computations, must be examined.

The lower curve on Fig. 64 shows that portion of DOC attributable to aircraft price (depreciation, insurance, and spares). It steadily decreases with increasing gross weight. An interesting factor is the percentage of DOC attributable to aircraft purchase price as a function of size, illustrated in Fig. 65. The ATA formula indicates an increase from 26.5% of DOC at the 91,000-lb DC-9-10 to 45.3% for the 747. The basic reason for the percentage increase with size is that, although these charges decrease when measured in cost/seat-mile or/ton-mile for the larger aircraft, the other elements of DOC, such as fuel and crew, are decreased even faster/seat-mile or/ton-mile by the larger aircraft. The effect of state-of-the-art improvements on price-related costs is illustrated by considering the 17.9 and 19.3% of DOC attributable to the price of the DC-7 and 1049G, respectively. It should be noted that the small percentages for these older aircraft are not so much because these costs are low, but rather because the other factors in DOC are high. Therefore, although larger modern aircraft have lower DOC's, these costs are now more sensitive to initial aircraft costs.

Additionally, DOC's are normally compared on an available seat-mile or ton-mile basis, that is, assuming a 100% load factor. For a fixed payload/flight up to the maximum payload of the smaller aircraft, a smaller aircraft will generate a lower DOC/flight and therefore a lower DOC/revenue seat-mile or/ton-mile. This means that larger aircraft are economically attractive only when they can be operated at load factors approaching those of the smaller aircraft. This can be achieved either by reducing frequency of service, or by generating more traffic with the increased capacity available and customer appeal of the larger aircraft.

Indirect Operating Cost (IOC)

Indirect operating costs are largely functions of the number and type of aircraft moved at a terminal or in the airspace, the total passengers or tons moved per day, and the peak movements of both. The factors for which this relationship is not necessarily true—advertising, general, and administrative costs—normally amount to only a small portion of IOC. Therefore, IOC is dependent on specific situations, and historically has ranged from 50 to 100% of DOC for U. S. airlines. If the airspace and runways are at or near saturation, as is frequently the case at many hub airports today, larger aircraft at lower frequencies will tend to expand the flow capacity of cargo or people to and from the terminal. The terminal throughput must, of course, be expanded to match. Occasional large aircraft, however, create peaks in demand for ground personnel and facilities beyond that required for a steadier flow of smaller aircraft.

When traffic warrants larger aircraft at fairly high frequencies, on the other hand, they justify a degree of automation and mechanization in passenger and cargo handling which greatly reduces the manpower content per unit handled in those tasks. At high flow rates, these economies of scale can result in significant savings.

Another significant aspect of size occurs in cargo aircraft when straight-in loading can be accomplished through the nose without disturbing the flight station. The expansion in the amount of air-eligible cargo by virtue of straight-in loading can be substantial and the loading cost savings are significant for even routine shipments. But it is lighter and simpler to open the cargo compartment at the fuselage nose below a fixed flight station than it is to open the aft fuselage with doors or by swinging the tail. Airplane size needs to be great enough to permit this nose innovation, and the results appear indirectly in DOC because of a lighter airplane and directly in IOC through decreased loading costs.

Implications

With the development of the jumbo jets, the industry has reached the point at which decisions to increase size in commercial transports can be made with slightly less emphasis on DOC. Size selection should be influenced heavily by the probable load factors achievable with larger aircraft, and the effect of larger aircraft on total operating costs, including IOC. The objective is profit or, more particularly, return on investment, not low DOC's as such. Each new large aircraft continues to demand careful analyses of total cost and risk to select the optimum balance between increased size and technological improvements to achieve increased economy simultaneously with increased capacity.

IX. Projections

The useful-load of large, current-technology cargo/passenger aircraft is 50–60% of the design gross weight, depending upon range and on other design and operating requirements. At C-5A state-of-the-art, and meeting the same requirements, doubling the C-5A gross weight would have increased the absolute useful load while reducing the useful-load fraction about 10%, as indicated on Fig. 6. There are, however, a variety of options for increasing both the useful load and the load fraction of the next generation of aircraft. A certain increment of useful load can be achieved by many combinations of technology and gross weight. Some potential increases resulting from application of advanced technology, discussed subsequently, are summarized in Fig. 66, which is an enlargement of a portion of Fig. 6.

Structural Weight Reduction

The development of advanced composite materials has shown that, even in first-generation applications, weight reductions of 20–25% can be realized in structure. Studies of advanced designs wherein the cascading effects of lighter structure permit smaller engines, which in turn permit still smaller and lighter structure, reveal even greater savings, indicating that structural weight reductions of the order of 30% will be possible in the near future. Applying advanced materials and structural technology to a next-generation transport for the same design gross weight as that of the C-5A could produce about a 13% improvement in the useful-load fraction to a value of 0.63, as shown by the triangular symbol in Fig. 66.

As discussed in Sec. V, each successive increase in size of aircraft has tended to aggravate old stiffness problems and to reveal new ones. Those which are related to the basic dynamic response of the structure—wing bending and torsion, for example—will undoubtedly benefit from the large-scale utilization of high-modulus composites, which can be expected to afford a refreshing relief from stiffness problems. Currently available composites have moduli of $40\text{–}50 \times 10^6$ psi in unidirectional properties, and higher values are expected. Even in the currently more practical cross-ply design concepts, values approaching 20×10^6 psi are achievable, twice as high as aluminum. As a matter of fact, the first generation or two of aircraft with a high content of filamentary composites will perhaps demand almost no weight attributable to aeroelastic problems of any kind, unless the new optimal aspect ratios are so much higher and section thickness ratios so much lower that they consume the stiffness margin.

Today's technology offers such high-strength steels as H-11, D6AC, and 300M, whose ultimate tensile strengths approach 300,000 psi. Development is proceeding rapidly toward 350,000 psi in the maraging steels, and even 400,000 psi is projected for the immediate future. Such materials seem adequate to keep up with the needs for ultra high-strength parts of new and bigger aircraft. After some thirty years of limited usage, titanium is coming into increased favor. Now at about the 10% level, the techniques of diffusion bonding, currently under intensive development by the Air Force and several airframe manufacturers, promise to significantly broaden the range of practical applications. Similarly, the development of extruded shapes is opening another large category of titanium applications.

On the negative side, the trend in new materials supporting the continual evolution of larger aircraft includes potential problems in crack-propagation characteristics. Annoying, yet relatively minor, with such crack-tolerant materials as 2024 aluminum, it may not be so minor in some of the new high-strength materials, including perhaps the high-modulus composite materials, which are quite brittle. Solution of this problem is mandatory before such new materials can be considered really available.

A number of other areas of progress should contribute to the over-all structural advance. Although mechanical fasteners still can be improved, the major steps will be in bonding and in bonding combined with welding or mechanical fastening. In any event, a great deal of development must occur in fastening systems to exploit fully the new composite materials.

All of the previous applies to conventional configurations and structural proportions, but can be affected by changes in design concept which may be associated with size growth. New materials tend to change optimizations in aspect, taper, and thickness ratios; in engine locations; and in stabilizing and trim surfaces, among others. More avionics in flight control and more stability augmentation put more of a premium on low-inertia surfaces, permit some surface size decrease, and ultimately will affect civil and military rules and limits so as to alter structural design loads in both distribution and absolute value, hopefully in a direction favorable for structural weight. Unconventional configurations, described later, can have profound effects on structural weight fractions; a canard surface is helpful and an all- (or mostly all) wing configuration introduces radical differences in this respect.

Aerodynamic and Propulsion Improvements

The combined effects of technological advancements in aerodynamics and propulsion for the next generation of aircraft should produce an additional 10% improvement in the useful-load fraction over that obtained from advanced materials. The resultant 24% increase in useful-load fraction over that of the C-5A (up to 0.69 total) is shown by the square symbol on Fig. 66. Although the separate contributions of these two technologies are not directly additive, it is appropriate to review the predicted advancements in these areas together.

The next decade will probably see important but evolutionary improvements in propulsion-system technology. The growing emphasis on STOL capability and low noise generation, coupled with the desire for improved cruise specific fuel consumption, favors continued turbofan development. Progress toward stoichiometric turbine-inlet temperatures, achievable with improved materials and more efficient cooling of turbine blades and stators (perhaps by transpiration) will continue to reduce gas-generator specific weight. Compressor pressure ratios approaching 40 are foreseeable, with the associated benefits of improved thermal efficiency and specific fuel consumption. With higher-energy gas-generator systems, further advances in propulsive efficiency may be accomplished effectively with still higher bypass ratios, which may reach the 20–30 range for some STOL applications. Engines such as these may prove to have applications as pitch-trimming devices—jet canards—on non-STOL configurations requiring large trim moments only when high-lift devices are deployed.

It is probable that turbofan specific weights can be held to present values, or improved slightly, for these higher bypass ratios, while improvements in thermal and propulsive efficiency will reduce present subsonic cruise specific fuel consumptions by 10–15%. Sens and Meyer[18] provide a good and more detailed projection of anticipated advances in engine technology for the next ten years or so, forecasting an engine called a "possible JTND" of pressure ratio 40, bypass ratio 12, cruise turbine-inlet temperature 2500°F, and 100,000-lb takeoff thrust. Four such engines could power a conventional 1.6 million-lb transport with a 0.60 useful-load fraction at Mach 0.8 for 4200 nautical miles, carrying a 500,000-lb payload.

In the long term, major improvements in over-all aircraft efficiency will be accomplished by continued exploitation of engine/airframe integration and the opportunities provided by larger aircraft size. Use of low-drag boundary-layer control concepts, for example, may minimize the relative weight of the power plant, the absolute weight of the power plant, and the size of the aircraft required to deliver a given payload. Dawson and Holliday[19] make some detailed prognoses in this area, including the suggestion that boundary layer control may lead back to smaller engines (pumps) of greater number distributed about the aircraft complementarily with the suction systems; this possible engine-size trend reversal is interesting. It is almost a paradox that the astonishingly high reliability of turbine engines opened two converse avenues: reduction of number of engines below four is now very practical from a safety viewpoint, and increase of number of engines above four is now practical from an operational and maintenance viewpoint. The use of variable-pitch fans and Rostat aft fans, unorthodox engine installations, and methane as a fuel may afford significant advantages; both the Dawson/Holliday paper and R. H. Weir's 16th Barnwell Memorial Lecture[20] explore these possibilities in some depth and offer excellent discussions on the possible futures of propulsion, occasionally probing as much as 50 years ahead.

Several aerodynamic trends are foreseen which will help offset size adversities of tomorrow's larger aircraft. The effectiveness of high-lift systems can be expected to continue to increase, thereby allowing greater wing loadings and smaller

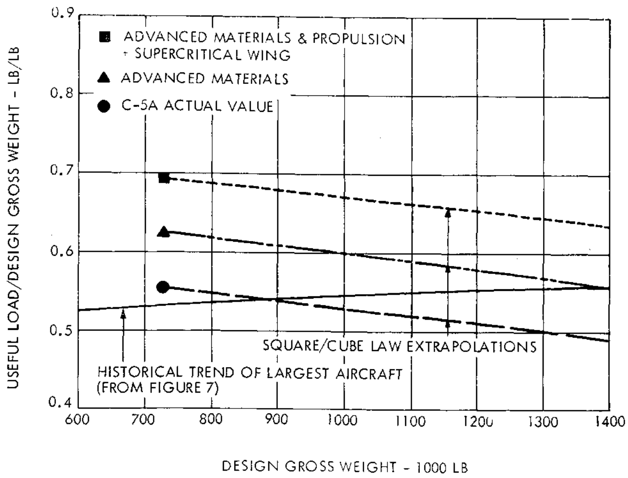


Fig. 66 Useful-load fraction at various technology levels.

wings on aircraft of the future. Supercritical airfoils will afford up to a 10% improvement in the product of Mach number and lift/drag ratio over the earlier 6-series airfoils. This advantage may be utilized to allow reduction in wing sweep and/or an increase in wing thickness at a given cruise speed. Reference 21 covers recent progress in this area.

The flight-control system can be utilized to alleviate air loads due to gusts or maneuvers, as well as to reduce dynamic loads associated with structural modes excited by control or external inputs. The trend toward ever increasing reliance on flight control avionic sophistication for very large aircraft implies that the aerodynamic advantages of canard surfaces for trim and control will eventually be employed, perhaps with complete reliance on artificial stabilization to provide satisfactory flying qualities. The entire concept of "mostly-wing" configurations leans heavily on avionic flight controls; both in cruise, particularly recognizing the problem of chordwise shift of the center of pressure, and in airport proximity, because of the probable large trim changes resulting from the high-lift system.

The fact that the profile drag of existing aircraft is closely approaching the skin-friction theoretical limit for turbulent flow suggests that further decreases in drag through contour refinements are unlikely. The work of Pfenninger at Northrop, Raspet at Mississippi State University, Lachmann at Handley Page, and others, has shown the large drag reductions through boundary-layer suction mentioned earlier, but the accompanying manufacturing complexities discourage application of these principles. An enormous potential interaction exists with the aircraft structural concept in order to optimize an arrangement of slots or slits, ducts, load-carrying structure, pump installation, means to avoid acoustic tripping of the boundary layer, fuel-tank integration, and other new features associated with this concept. And of course the optimum (low) wing loading with boundary-layer control reverses the trend toward higher loading in conventional arrangements.

For the sake of completeness with respect to operations on the boundary layer, continuing research into the concept of compliant skins may one day prove fruitful.

Several laboratories are working on the concept of reducing the penalty imposed on the manufacturing cost and weight of future aircraft by aerodynamic contour requirements, while maintaining existing minimum-drag standards. This is done through application of the locked-vortex principle to abrupt changes in contour or surface discontinuities. The vortex action retains flow attachment in the face of severe departures from normal aerodynamic practice, and may open the way for design compromises in tomorrow's even larger aircraft that are more in favor of structures and manufacturing cost with tolerable aerodynamic penalty.

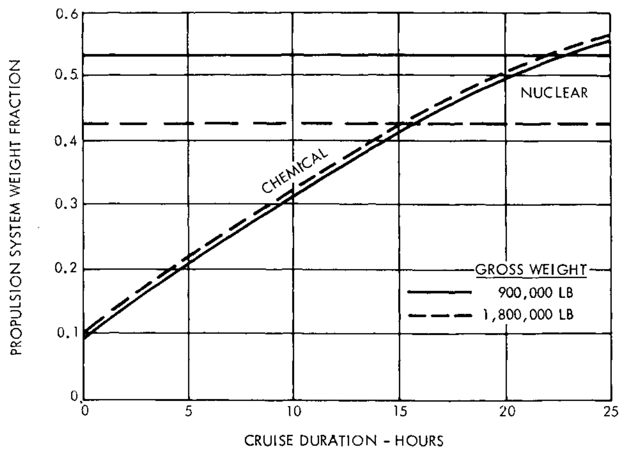


Fig. 67 Comparison of nuclear and chemical propulsion.

Systemic Advances

Several flight-control system possibilities have been discussed. Although relatively small, and thus not shown on the scale of Fig. 66, important reductions in the weight of other systems are anticipated through further increases in unit capacity.

In the general area of landing-gear improvements, graphite brake energy-absorption materials can be expected to reduce weight by more than 20% below the level already achieved through the use of beryllium.[22] Tires which can be deflated for stowing promise to reduce landing-gear bay or pod and door size, associated actuation-system power, and drag.

Improvements in materials require the re-examination of hydraulic system pressures because of the potential reduction in system weight as the pressure increases. Both reliability and maintainability must be examined, however, to establish whether an increase in pressure would be really cost effective.

As the aircraft size increases, the disproportionate part of the total system weight attributable to the power transmission system suggests utilization of a number of power centers, each of which may utilize local energy storage. A companion to this technique is the further development of integrated servo packages in which the hydraulic power-generation and aerodynamic surface-actuation equipment are contained in a single package at the aerodynamic-surface control. One of the most promising areas for increasing reliability is through use of fluidics for computational, control, and actuation functions. Fluidics systems have few, if any, moving parts and are extremely tolerant of variations in environment.

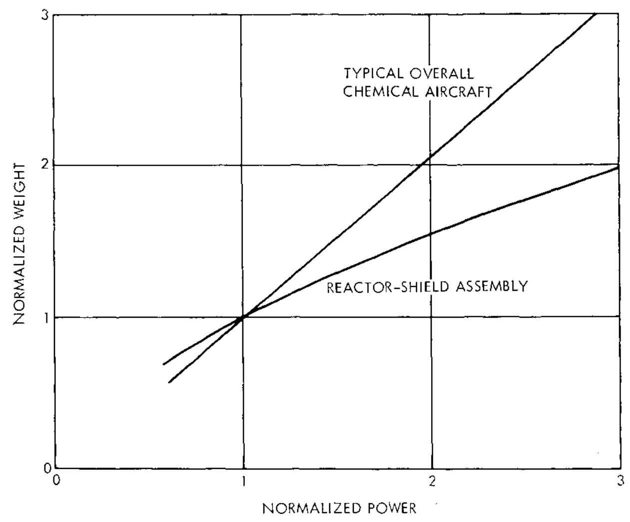


Fig. 68 Comparison of weight/power for nuclear and chemical propulsion.

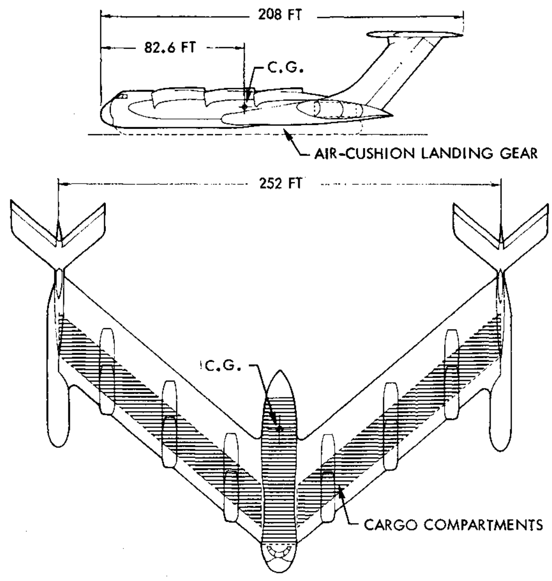


Fig. 69 Spanloader.

The electrical systems, like the hydraulic systems show the greatest potential for weight reduction in the area of power and control-transmission systems; that is, wiring. A proven technique having some further promise is an expansion of the application of multiplexing electrical signals, which has already demonstrated weight savings of several hundred pounds on some current large aircraft.

Nonconventional Concepts

The configurations and power plants discussed previously for large aircraft relate to improvements in a continuum of conventional designs. As aircraft become very large, however, concepts such as nuclear propulsion and flying-wing configurations become eligible for reconsideration.

Nuclear technology has progressed significantly since the demise of the Aircraft Nuclear Propulsion (ANP) program in the 1950's. This results in longer lifetime nuclear fuel; lighter, more compact shielding; improved heat-transfer systems; and aircraft and engines large enough to be compatible with nuclear propulsion.

Percentage of fuel burnup has more than quintupled, reducing reactor core size for a given power level and lifetime. This permits a significant reduction in reactor-shield assembly weight. Advances in shielding technology include the change from the divided shield to a unit shield with all of it at the reactor, eliminating exposure of the public to radiation hazards; new shielding materials; and computer techniques permitting more sophisticated, lighter weight designs.

In the Space Nuclear Auxiliary Power (SNAP) programs and the Lithium-Cooled Reactor Experiment (LCRE), solutions have been demonstrated to problems in design, development, fabrication, and internal corrosion of liquid metal heat-transfer systems. The problem of oxidation on the air side of the engine heat exchanger now only requires determination of the temperatures and lifetimes that are attainable with today's materials. Aircraft and engines large enough to fly on nuclear heat are now available. A reactor of sufficient power for cruise with a low dose rate unit shield will fit in a C5A fuselage; engines only slightly larger than the TF39 are required.

To match the 195,000-lb payload capability of a current chemically powered airplane at 4000 naut miles range, the gross weight of a nuclear-powered airplane with today's technology would be about 1,450,000 lb. As shown in Fig. 67, the potential advantages afforded by nuclear propulsion are increased steadily as aircraft gross weight and cruise endurance are increased. Since the development time for even a first-generation nuclear propulsion system up to flight test is probably of the order of 8–10 years, extrapolations of chemical vs nuclear aircraft comparisons become rapidly fatuous, but the inherent characteristics of reactor and shield weight/unit power improve so powerfully with increased design power level that they constitute essentially a repeal (at least) of the square/cube law. This is shown in Fig. 68 where the Reactor and Shield Assembly (RSA) weight grows as the 0.625 power of reactor design power ratio, which is nearly proportional to aircraft gross weight. The rest of the airplane empty weight, on the other hand, grows slightly faster than the first power of gross weight ratio, here plotted as power output in accordance with the weight/power proportionality mentioned. When this phenomenon is combined with other technological advances for any aircraft, the probable optimization level for gross weight can easily approach 5 or 10 million lb, depending heavily on the mission application.

A broad discussion of the status of technology for nuclear-powered aircraft is given in Ref. 23. The safety and economic considerations of nuclear aircraft are explored in Ref. 24.

The possible attractiveness of "mostly-wing" configurations was implied earlier. A conceptual approach is illustrated in Fig. 69. As shown by the shaded area, the wing is sufficiently thick to house a major portion of the cargo—hence the designation "Spanloader." A useful-load fraction of 0.77 is estimated for a gross weight of 1,200,000 lb. This high efficiency is attained by combining the effects of the uniformly distributed relieving load of the cargo inside the wing with the structurally beneficial characteristics of a 20% thickness ratio, and by exploiting composite materials. Another feature contributing to the low structural weight is the air-cushion landing gear located at each wing tip and at the central body.

In order to attain a cruising speed between Mach 0.75 and 0.80, it is necessary to combine a high angle of sweep with a supercritical airfoil section. Despite the relatively low effective aspect ratio of 6, the cruise lift/drag ratio is 20. Cost analyses indicate that such an airplane would permit air cargo DOC's as low as 1.5 cents/ton statute mile.

Although the airplane pictured includes high-lift boundary-layer control, the Spanloader concept appears to be a natural application of low-drag boundary-layer control. A problem with such a system is generally that it is heavy and difficult to install for fuselage suction and that it does not work too well at the intersections of aerodynamic surfaces. Also, it tends to push the optimum wing loading down and the power loading up. All of these characteristics are very compatible with the Spanloader. The adverse structural and systems weight for the suction system would probably be much more tolerable because of the compensating advantages, and an excellently balanced combination appears to result simply because absolute size and certain technological advances conspire to permit a new configuration concept that would otherwise be impractical.

Concluding Remarks

There is a new economic and operational element in commercial air transportation that is, so far, unquantified. As more and more traffic congests the airway and airport system, a substantial relief is afforded (for a fixed total amount of cargo or number of passengers to and from an airport) by larger aircraft if airspace assigned to them is little larger and the frequency of landing or taking off is materially unchanged. If the pressures of traffic delay continue to grow—certainly if traffic priorities are assigned according to payload size—a new and important forcing function toward growth will have emerged.

It is evident that there are no fundamental technical reasons why aircraft cannot continue to grow in size. The question, rather, is whether the mission or task requirements can justify these larger aircraft economically within any special and inviolable weight and dimensional constraints imposed by the ground system interface. Since a trend derived from the application of the square/cube law does indeed exist for major structural components and major systems at any particular state-of-the-art, its effects in the future must continue to be offset through advances in aerodynamic, structural, propulsion, and systemic technologies. In addition, time for these advances must be available, compatible with the size-growth timing sought.

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Evaluation of the Design Parameters for Optimum Heavily Loaded Ducted Fans

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A consistent mathematical model for the ultimate vortex wake system of an optimum heavily loaded ducted fan has been developed for zero hub diameter and neglecting compressibility, viscosity, and tip clearance. The compatibility relationships to be satisfied are presented with a brief description of the model. For any choice of blade number and pitch angle, it is shown that the blade bound vortex strength distribution for the heavily loaded ducted fan may be extracted from the lightly loaded case through the use of a simple scaling factor. In addition, expressions are developed for the power, thrust, and induced efficiency for the heavily loaded system which may also be extracted from the lightly loaded results. Some sample results are presented for a ducted fan with 2, 4, 6, and 8 blades with loadings from a light load to the static thrust condition.

Nomenclature

b = number of blades
B_1 = defined as an integral, Eq. (16)
B_2 = defined as an integral, Eq. (17)
C_p = power coefficient, $C_p = P/\rho(\Omega R)^3\pi R^2$
C_T = thrust coefficient, $C_T = T/\rho(\Omega R)^2\pi R^2$
E = energy loss in the wake
e = nondimensional energy loss, $e = E/\rho(\Omega R)^3(\pi R^2)$
$f(t)$ = a function of time
G = scaling factor, Eq. (23)
$K(x)$ = nondimensional blade bound vortex strength distribution, Eq. (31)
L = characteristic axial length in wake, $L = 2\pi R\lambda/b$
$\bar{P}$ = nondimensional distance from a vortex element to a control point
p = static pressure
p_∞ = freestream static pressure
p_0 = total pressure
Q = torque
r,Ψ,z = cylindrical coordinates
r',Ψ',z' = cylindrical coordinates defining location of vortex filament
r,ξ,ζ = helical coordinates
R = blade tip radius, wake radius
S = surface area
dS = elemental surface area
T = total thrust of ducted fan
t = time
u = disturbance velocity in direction of subscript
u_{vs} = induced velocity, at $\bar{w} = 0$, associated with the inner helical sheets and the nonuniform boundary sheet
u_{ξ_0} = disturbance velocity component along wake axis
u_R = disturbance velocity component at inside of wake boundary
u_{ζ_B} = velocity component normal to filaments of the uniform boundary sheet
v = total disturbance velocity
V = velocity in ultimate wake
V_R = velocity at inside of wake boundary
V_∞ = axial flight velocity
w = apparent axial displacement velocity of blade trailing vortex sheets
$\bar{w}$ = nondimensional displacement velocity, $\bar{w} = w/\Omega R$
x,y,z = cartesian coordinates
x = nondimensional blade radial station, $x = r/R$
z_0' = distance between the $z = 0$ plane and the point where the filament intersects the xz plane
β = angle between the normals to the vectors $d\bar{s}'$ and $\bar{P}$ measured in the plane determined by $d\bar{s}$ and $\bar{P}$
$\Gamma(x)$ = blade bound vortex strength distribution
γ = a vortex filament strength
$\gamma(\zeta_B)$ = strength of boundary sheet at its lines of intersection with inner sheets
γ_i = vortex filament strength of finite unknown strength filaments replacing sheets of wake
$\bar{\gamma}_i$ = nondimensional filament strength, Eq. (27) $\bar{\gamma}_i = \gamma_i/(4\pi RwG)$
ϵ_0 = numerically integrated factor for $\bar{w} = 0$, Eq. (39)
κ = mass coefficient, $\kappa = 2\int_0^1 K(x)\,xdx$
λ = tangent of helix pitch angle of inner sheets $(V_\infty + w)/\Omega R$
λ_B = tangent of helix pitch angle of boundary filaments at their lines of intersection with inner sheets $(V_\infty + w_B)/\Omega R$
ρ = fluid density

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