LTA Aerodynamic Data Revisited

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Nomenclature

$\bar{a}_T$ = effective tail lift curve slope, calculated in various ways: $\bar{a}_{T_0}$ = slope near zero angle of attack; $\bar{a}_{T_{10}}$ = slope based on lift coefficient change from 0 to 10° angle of attack; $\bar{a}_{T_D}$ = determined from damping experiments assuming tail force is located at λ from center of buoyancy
AR = aspect ratio, span of surface squared divided by area
C = resistance coefficient, $C = \text{drag}/\rho V^2 (Q)^{2/3}$
C_D = drag coefficient, $C_D = \text{drag}/q(Q)^{2/3}$
$C_{D_{\text{wet}}}$ = drag coefficient based on surface area, $C_{D_{\text{wet}}} = \text{drag}/q\, S_{\text{wet}}$
C_L = lift coefficient, $C_L = L/qQ^{2/3}$
C_{L_T} = tail lift coefficient based on tail area, $C_{L_T} = L_T/qS_T$
$\bar{C}_{L_\alpha}$ = hull lift curve slope based on maximum cross section area of hull, $\bar{C}_{L_\alpha} = L_\alpha / q(\pi D^2/4)$
C_P = pressure coefficient, $C_P = \Delta p/q$
C_M = pitching moment coefficient, $C_M = M/qQ^{2/3} l$
D = maximum diameter of airship, ft
FR = fineness ratio, length divided by diameter
I = moment of inertia of airship including virtual inertia, slug-ft^2
I_A = moment of inertia of airship alone about vertical axis, slug-ft^2
l = airship length, ft
L_T = tail lift, lb; the tail lift (or side force) is determined in two ways as noted: 1) pressure measurements, integration over tail surface; and 2) force measurements, the difference between hull and tail force, and the bare hull force. This second method includes the "carry over" lift.
m_x, m_y = mass of airship including virtual mass in direction indicated by subscript, slugs
n = normal force loading, lb/ft
N = yawing moment, lb-ft, positive tending to turn nose right
p = static pressure, psf
q = freestream dynamic pressure, psf $q = \frac{1}{2}\rho V^2$
Q = volume, ft^3
r = yaw rate, rad per sec
R = radius of turn, ft
Re = Reynolds number based on length of airship, $Re = Vl/\nu$ or as noted
S_T = total tail planform area (vertical or horizontal), ft^2
S_{wet} = total surface area, ft^2
V = freestream velocity, fps
x = longitudinal distance from nose, ft or longitudinal axis
y = lateral axis
Y = side force, lb, positive to right
α = angle of attack, rad or deg
β = sideslip angle, positive for relative wind from the right, rad or deg
δ = boundary-layer thickness, in
δ_e = elevator angle
δ_r = rudder angle, positive for trailing edge to the right
λ = effective tail length from center of buoyancy, ft (experimentally determined by dividing $\partial N^T/\partial\beta$ by $\partial Y^T/\partial\beta$
ν = kinematic viscosity of air, ft^2/sec
ρ = air density, slugs per ft^3
ψ = heading angle, positive to right
$(\ )_M$ = model
$(\ )_{FS}$ = full scale
$(\ )^H$ = hull only
$(\ )^T$ = tail only
$\dfrac{\partial Y}{\partial r}, \dfrac{\partial N}{\partial r}, \dfrac{\partial N}{\partial \beta}, \dfrac{\partial N}{\partial \beta}$ = stability derivatives
$(\dot{\ })$ = first derivative with respect to time
$(\ddot{\ })$ = second derivative with respect to time

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Introduction

A GREAT deal has been written and claimed for lighter-than-air vehicles over the years. Currently, we are witnessing a major resurgence of interest in these machines largely because missions for which they appear to be suited have come to the fore in both military and commercial spheres. Innumerable studies of potential configurations and methods of operations have been, and continue to be, conducted. Widely divergent as many of these studies may seem, they all share a common element: perforce they must depend upon data generated and recorded many years ago, generally obtained with experimental facilities and techniques that, by present day standards, leave much to be desired.

It is probable that none of the primary conclusions of these studies is so sensitive to the magnitude of any one of the parameters selected as to be reversed by a major change in its value, but it is not at all unlikely that more than a few problem areas may be obscured by the cumulative effect of over- or under-estimation of a number of aerodynamic coefficients and stability derivatives.

If this development of modern lighter-than-air devices is to proceed with a reasonable level of confidence, it would appear that three major questions must be answered: What do you want such machines for? What do you need to make them work? How do you obtain the necessary information? An appreciation of the quantity and quality of the aerodynamic investigations conducted to date is necessary if the designer is to attempt to formulate responses to these questions.

A number of specific applications have emerged as answers to the question of why lighter-than-air vehicles may again find practical aeronautical usage. A strong case can be made for high altitude maneuverable vehicles capable of maintaining a given position with respect to the Earth's surface for protracted periods of time for use as what are essentially low altitude stationary satellites. Machines designed for an ultra-heavy lifting capability can be envisioned fulfilling various construction and transport functions or being utilized for such tasks as ship loading and off-loading. If capable of sufficient speed and endurance, similar vehicles may be ideal for a number of military missions, particularly in the anti-submarine warfare field. Craft intended for operation at altitudes somewhat below the tropopause also may have a military role to play as special weapons platforms. The factors leading to the consideration of lighter-than-air machines for such applications are the required lifting capabilities of greater magnitude than current or projected rotor technology can produce in a cost effective manner, and, for many missions, an endurance measured in days or weeks rather than hours.

In order to predict the characteristics of these vehicles, one must be able to estimate the magnitude of the aerodynamic forces and moments acting upon them. Such predictions have reached a high degree of reliability in the case of conventional heavier-than-air machines, owing to a vast body of constantly updated empirical data backed by well-developed analytical and computational techniques. A similar statement cannot be made about lighter-than-air craft. These machines tend to be of a size, shape, and mass distribution that is of a different scale altogether from conventional airplanes, and require extrapolations to Reynolds number ranges, wetted areas, and vehicle response rates quite unfamiliar to the modern aerodynamicist.

Compounding the problem are the facts that not only are the sources of information providing data relating to the aerodynamics of airships much less numerous than those dealing with aircraft, but most of the reports making up the body of this literature are also 40 or more years old, dating from a period when much wind tunnel and flight test instrumentation was fairly rudimentary. However, short of conducting contemporary large scale tests (probably a prohibitively expensive procedure), there is no other source of information available to the aerodynamicist. This is a survey of what appeared to the authors to be the most significant elements of the literature, along with a critical evaluation of their probably accuracy.

As will be seen from the bibliography, many of the references cited report work carried forth in England between 1919 and 1930. The quality and volume of this work quite surpasses that conducted elsewhere, although some useful investigations were conducted in the United States by the NACA and the Guggenheim Airship Institute. Unfortunately, the conduct of English airship research terminated abruptly with the R 101 disaster. The authors have not been able to obtain German literature with the exception of Refs. 1, 2, and 3 which are translations providing considerable information, but lacking detail. The large scale data points which are available date from the development of the airships Akron and Macon. Reference 4 is readily available and of excellent quality and scope and is recommended to readers with further interest in the subject of this survey.

About 20 years ago, a few investigations relating to improvement of nonrigid airship performance were conducted. Two interesting studies were the full scale boundary layer measurements on an airship,[5] and the aft mounted propeller installation tests reported in Ref. 6. A study of the effect of shifting part of the lifting force from the envelope to the fins was conducted as a Master's thesis at Princeton University[7] demonstrating a marked performance improvement, in a sense pointing to the potential of hybrid designs. Lifting body work conducted by NASA provides much of the insight about the aerodynamic characteristics to be expected from some proposed hybrid configurations, but in this survey, the authors have restricted attention to essentially fully buoyant craft employing conventional airship shaped hulls of more or less circular cross section and fineness ratios in the range of 3 to 10.

Drag Aerodynamics

The early history of airship drag studies is basically a history of methods of interpreting and applying experimental data and empirical techniques to the prediction of full-scale airship drag. The history is made more interesting to the observer, although more agonizing to the participants, by a parallel effort to obtain and interpret full scale flight data to determine the actual drag values. It was not until the last decade of serious airship effort that significant progress was made in the understanding and application of theoretical prediction techniques to the problem of determining airship drag. Also, it was not until this last decade that instrumentation, testing, and data interpretation techniques were developed to the point where reasonably precise full scale flight measurements of airship drag could be made.

An historically ignorant, but technically informed reader of airship literature, particularly that prior to 1930, is struck with the seeming paradox of noted workers in aerodynamics baffled by, or at least uncertain of, the correct interpretation of aerodynamic drag phenomena. This is particularly true with regard to wind tunnel tests of airship models, most of which were performed at Reynolds numbers where significant parts of the bodies could be expected to have a laminar boundary layer. This apparent lack of understanding is partially explained by the historical correlation of airship development and aerodynamic theory shown in Fig. 1. From this figure, we see that at the beginning of the 20th century (when the Europeans were doing their early airship development) the viscous drag aerodynamicist had at his disposal little more than the Navier-Stokes equations and Reynolds' experiments with dye filaments in pipes. The concept and description of a boundary layer were not published by Prandtl until 1904, and the Reynolds number was not given a name until almost 1910. The concept that boundary-layer conditions could seriously influence not only viscous drag, but pressure drag as well, was not recognized until the second decade of the 20th century when discrepancies in the measurement of sphere drag were studied by Prandtl. It is not surprising that early German and British airship drag measurements on models were subject to misinterpretation. All of these craft were typically so long and slender that form drag was small and skin friction drag clearly predominated. Thus, anything affecting boundary-layer conditions such as test Reynolds number, tunnel turbulence, and model roughness would be expected to have a large effect on drag measurements; and the lack of an adequate theory to explain the observed phenomena understandably left an air of mystery.

The problem is illustrated by Jones in his excellent R 38 Memorial paper[8] in 1924 in which he reviews and discusses British airship aerodynamic studies to that date. He refers to the influence of model roughness and tunnel turbulence on the measured model drag, and to unexplainable trends with Reynolds number. This is not too surprising in the light of Fig. 2 which shows what we know is the variation of the drag coefficient of bodies of revolution with *Re*. The model tests were in the transition range of $Re \sim 10^6$-10^7. Five years later in Ref. 9, Jones describes some aspects of the importance of the boundary layer, but it was more than 20 years later that the concept of boundary-layer stability and transition from laminar to turbulent was adequately described theoretically.

Coincidence also played a role in deluding investigators of this era. Table 1 from Ref. 8 compares airship drag coefficients obtained from model experiments with full scale data obtained from deceleration tests and shows quite good agreement. Virtual mass effects were neglected in the analysis of full scale data. One can only agree with Jones' conjecture that the combinations of scale effects, incomplete model simulation, flight test vagaries, and lack of consideration of virtual mass effects in the full scale deceleration tests produced this misleading result. The importance of virtual mass effects was not unknown at the time; Lamb[10] had published expressions several years earlier for ellipsoids, and Munk[1] had applied corrections to German flight test data. By correcting the full scale data for virtual mass (Jones estimated a factor of approximately 15%), the results agreed with another set of model data obtained by adding large scale component contributions to small scale bare hull data also shown in Table 1. Faced with such a dilemma, one can only conclude that investigators of the era were born 25 years too soon, and only time and adequate boundary-layer theory would resolve the issue.

The sans-theory empirical-experimental approach to airship drag prediction probably was culminated by Havill's[11,12] compendium of airship drag, performance summaries, and predictions published in 1926. Here, nearly every known airship's performance characteristics were systematically cataloged, nondimensionalized, and correlated to provide a systematic representation of their performance parameters. In the second of the two references, drag predictions were similarly systematically reduced to generalized empirical expressions that appeared to show the proper trends for form effects on skin friction drag; this approach is carried further in Ref. 13, but no results are given.

It was not until 1934 that an adequate theoretical explanation of boundary layer mechanics was developed, through the efforts of Millikan, von Karman[14] and others, that allowed both proper interpretation of scale model data and reasonably accurate theoretical predictions of hull drag. Also, by this time, model test facilities were available to extend model *Re* to nearly one-tenth full scale values. The best examples of these accomplishments are to be found in the NACA Reports,[15-18] documenting tests on a one-fortieth scale model of the Akson in the propeller research tunnel and various airship models in the variable density tunnel. In particular, the variable density tunnel results fill out the spectrum of drag as a function of Reynolds number to nearly full scale values for various airship shapes, and the results stated in Ref. 15 show that a workable boundary layer theory existed that would predict model friction drag even with both laminar and turbulent boundary layers present and thus, might be expected to predict model friction drag even with both laminar and turbulent boundary layers present and thus, might be expected to predict full scale friction drag with virtually all turbulent flow. The proper marriage here was an adequate theoretical representation of form effects on boundary-layer character combined with a statistical-empirical representation of turbulent boundary-layer momentum loss as given by Prandtl and von Karman, and later by Schoenherr. Results presented in Fig. 3 show very good agreement between theory and experiment.[15]

Complementing the advance in scale model testing and prediction techniques, considerable progress had been made by the early 1930's in full scale flight test measurements of airship drag.[19, 20] In the best documented of these efforts, flight tests of the Los Angeles,[19] considerable attention is given to correction of data for virtual mass effects (including a boundary layer mass contribution) and propeller drag as well as to the quality of velocity measurement instrumentation. To be sure, several unaccountable problems still existed in the performance of the tests and in the data recording. Specifically, it was difficult for the helmsman to maintain a level attitude owing to the false gravity caused by deceleration, and consequently elevator inputs were present in the data. The effects of elevator motion could be large if the data of Fig. 4[4] are at all representative. In addition, instrumentation time lags are not accounted for.[19] Burgess notes that although fast-response velocity instrumentation data were obtained with a well-calibrated instrument, these data were not used for the determination of deceleration. Instead, pitot-static pressure measurements with unknown time lags were used and the results compromised accordingly. It was realized that direct thrust measurements would circumvent the problems of deceleration tests, but these mechanisms generally were considered too expensive or complicated to implement.

Unfortunately, from the standpoint of comparing scale model and theoretical prediction techniques for airship drag with measured full-scale flight data, the model that was tested most exhaustively was the Akron, for which full-scale drag measurements apparently do not exist or are inadequately documented. Hoerner[22] presents a simplified approach based on flight test data from the Los Angeles that accounts approximately for form effects on both pressure and skin-friction drag and uses Schoenherr's empirical skin-friction representation for an all-turbulent boundary layer. After correcting for the engine nacelles, cab, and other components, it is concluded that, with the exception of some notable interference effects, airship drag can be predicted. This con-

Table 1 Comparison of model and full-scale drag values

	Resistance coefficient C					
Airship	Full scale deceleration tests virtual mass neglected	Small scale model C	Small scale model C_m/C_{fs}	Small scale model hull C	+	Large scale appendages C_m/C_{fs}
R-26	0.0248	0.0246	0.99	0.030		1.20
R-29	0.0227	0.0232	1.02	--		--
R-32	0.0199	0.0188	0.95	--		--
R-33	0.0173	0.0166	0.96	0.0197		1.14
R-38	--	0.0178	--	--		--

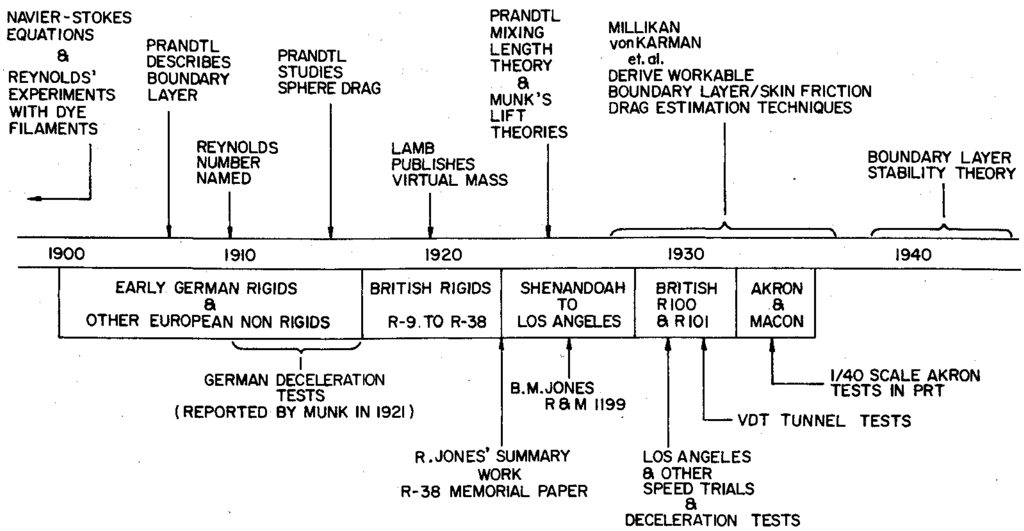

Fig. 1 Correlation of airship history and boundary-layer theory.

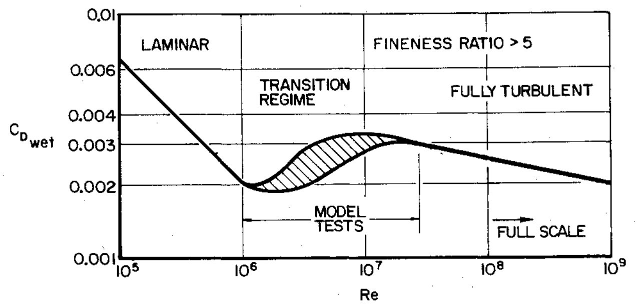

Fig. 2 Variation of drag coefficient of body of revolution with Reynolds number.[14]

clusion must be qualified, however, in view of the flight test and flight test data reduction procedures. It is probable though, that airship zero-lift drag prediction based on a proper combination of scale model tests and a theoretical/empirical correction was (as of 1935) more accurate than full-scale measurements by means of deceleration tests.

Aerodynamic drag considerations thus far have been restricted to skin-friction drag of the airship hull. From the standpoint of hull drag, this is proper since nearly all investigators have observed that at fineness ratios above approximately five, pressure drag due to form is practically negligible. Modern interest in BLC airships raises form drag considerations as being important, since one can reduce friction drag at constant volume with lower fineness ratios and then eliminate the separation-produced pressure drag by application of BLC techniques. Historical interest in influence of form is associated principally with form effects on skin-friction drag. Pressure drag was an important consideration on one airship, the ZMC-2, which had a fineness ratio of 2.8.

Hull drag is not the only contributor to the total profile drag, although it does represent between 50 and 75% of the total on most airships. Of the balance due to engines, engine installations, cab, rigging, accessories, and control surfaces, only the latter seemed to be a serious problem owing apparently to interference effects. This is illustrated in Table 2 where ratios of fin-to-hull area are compared to ratios of fin-to-hull drag values for various airships at conditions of zero angles of attack, sideslip, and control deflection. Some of the discrepancies indicated may arise from scale effects, but it is likely that much of the additional drag is due to interference effects of the fins on the body and/or vice-versa. Pressure data that might quantify these effects apparently were taken during the tests documented in Ref. 17; however, they also apparently were not published. Hence, more detailed accounting is left to modern investigators.

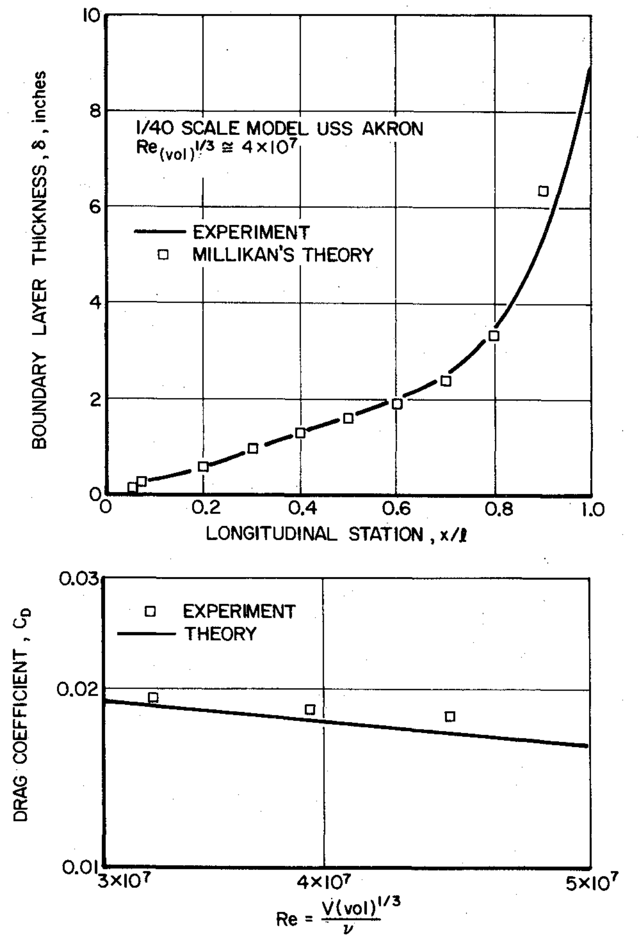

Fig. 3 Comparison of boundary-layer theory and experiment for friction drag of model airship hull.

The questions of induced and trim drag seldom are discussed in airship literature although many scale model measurements were made and documented.[16-18] The importance of these terms lies not only in their influence on airship performance, but also, from the point of view of correlating theory with experiment, on their influence on full-scale drag measurements. Referring again to Fig. 1, we see that Munk's theory[1] to account for induced drag was available for the last decade of large airship work but apparently was not used. One of the few commentaries on induced drag is found in Ref. 18 where it is observed that the

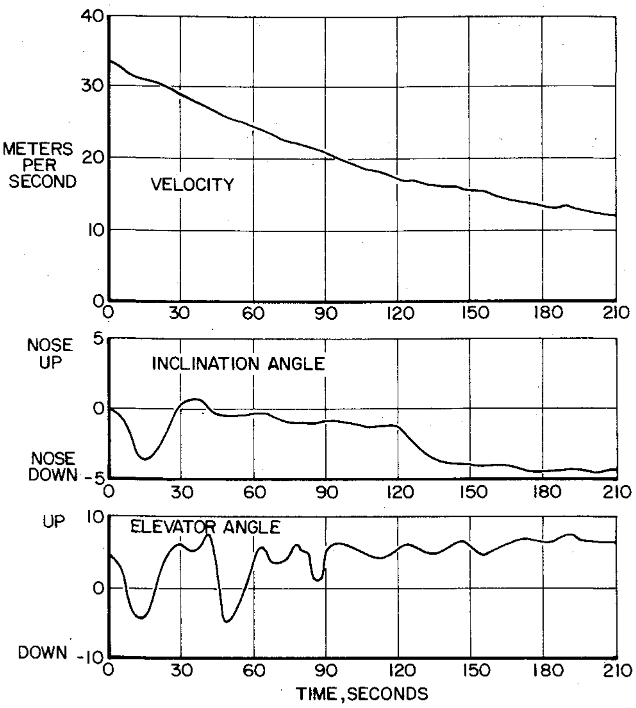

Fig. 4 Deceleration time history of large rigid airship.

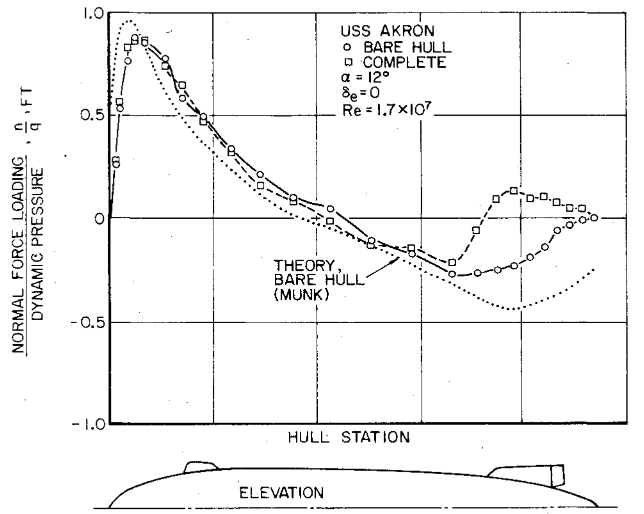

Fig. 5 Comparison of experimental and theoretical normal force loading on airship hull.

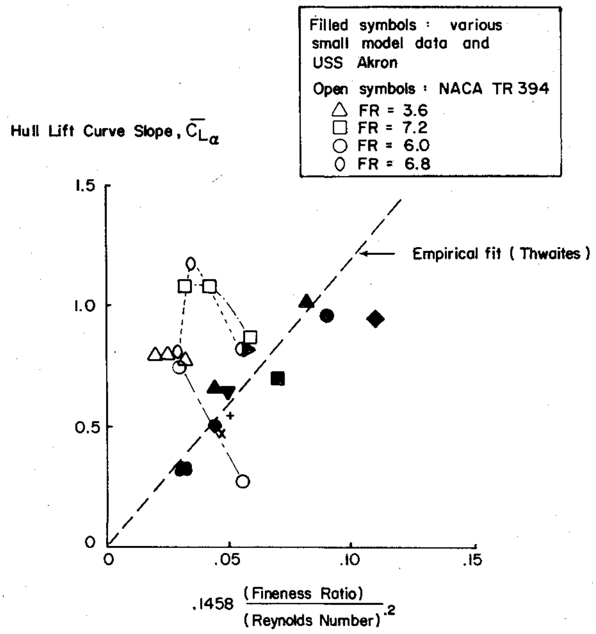

Fig. 6 Hull lift curve slope vs Thwaites' function.[16]

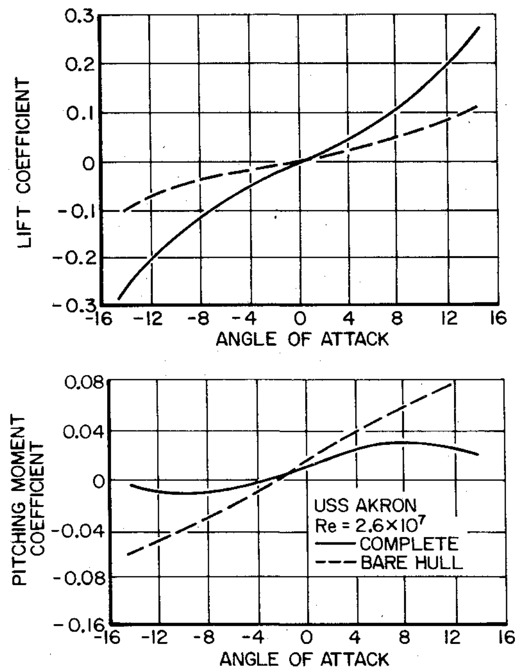

Fig. 7 Variation of lift and pitching moment coefficients with angle of attack.

"drag coefficients are at least at zero pitch. The rate of increase with pitch is small at small angles of pitch, but it becomes greater as the pitch increases." Hoerner[22] suggests that applications of Munk's slender body theory will predict induced drag; however, the lateral separation of the shed vortices must be predicted to define an effective aspect ratio. Hoerner also points out a strong dependence of vortex lateral separation on cross-sectional shape. Shapes like squares and triangles tend to force the vortices to shed at the corner discontinuity while smoother continuous cross sections like circles and ellipses allow a closer vortex spacing resulting in a lower effective aspect ratio.

To summarize the historical situation with regard to airship drag, it can be stated that the drag of the large rigid airships probably was not known to an accuracy of better than approximately 5%. On the other hand, drag prediction techniques utilizing accurate scale-model data and theoretical/empirical corrections were developed to the point that they could have been expected to yield drag values of accuracy at least comparable to full-scale tests.

Lift and Side Force Aerodynamics

Given the amount of experimental and analytical study that has been expended upon the aerodynamics and hydrodynamics of such shapes as missiles or torpedos, the literature is fairly rich on the topic of the steady state forces and moments created on such bodies by angles of attack or sideslip. As in so many other cases, however, data pertaining to the length-to-diameter ratios and shapes of interest to lighter-than-air craft are relatively scarce excepting perhaps in studies of modern submarine hulls, and there seems to be no satisfactory method of applying much of the existing information to airship shapes.

A complicating factor in the consideration of the dependence of the forces on sideslip or angle of attack is the nonlinear character for the basic shapes of interest. The potential flow theory developed by Munk[23] predicts neither lift nor side force, but correctly indicated the existence of an unstable moment. Experiments show that substantial forces are created, their rate of change with angle increasing with the magnitude of the angle as conditions depart further from those considered by potential flow, i.e., inviscid attached conditions.

Considering the question of force and moment generation of airship-like bodies without fins at low angles (α or $\beta < 5°$), Thwaites[24] states that there is "no generally accepted inviscid hypothesis corresponding to Kutta-Joukowski for airfoils." Fairly extensive experimental data have been taken on models at Reynolds numbers from 10^6 to 20×10^6, and at full-scale values, relating the normal pressures along the hull to the generation of force and moment. Although the correlation of the forces and moments computed from these pressures with total force and moment measurements varies from excellent to unsatisfactory, these pressure distributions do give an indication of the flowfield about the body.

Figure 5 presents a comparison of measured pressure distributions with that predicted by inviscid theory. The correlation between the two for the bare hull is quite good about the nose of the body, and poor downstream. Studies of the cross-flow fields of such bodies show that the longitudinal location of the onset of separation and the character and organization of the wake are strongly dependent upon both Reynolds number and angle of attack. At low angles of attack the wake tends to display disorganized turbulence, but as the angle is increased, a pair of strong vortices and their associated feeding sheets or vorticity appear.[4] The location of these vortices with respect to the body is dependent upon Reynolds number and body cross section shape. Early experimental data show a marked difference between a body with many stringers, approximating a circular cross section, and one fitted with a limited number of strakes to fix the separation point.[25]

Thwaites[24] gives an expression for the slope of the lift curve of airship hulls at small angles of attack (i.e., before the strong organization of the body of vortices, $\alpha < 5°$) as a function of fineness ratio and Reynolds number. As shown in Fig. 6, good agreement with a large number of experimental results was obtained. The data include high fineness ratio hulls of early English design, the Shenandoah[26] and the Akron[16]. However, additional results, from extensive tests conducted in the variable density tunnel[18] at Reynolds numbers from 10^6 to 25×10^6, show an opposite trend. The effect of body lift curve slope is generally of secondary significance when fins are added to the body; however, this discrepancy is typical of a number of areas in which prediction techniques are not satisfactory.

At higher angles of attack ($\alpha > 5°$), the influence of the organized wake vortices becomes dominant producing a more rapid increase of force with angle and a decreased sensitivity to Reynolds number. A typical variation of lift coefficient with angle of attack is shown in Fig. 7.

The pitching and yawing moments measured on airship-like bodies are generally smaller than predicted by inviscid theory as a consequence of the departure of the pressure distribution over the after portions of the body from the theory as shown in Fig. 5. Reference 18 indicates that the measured value of the pitching moment of hulls with fineness ratios between 3.5 and 7.2 at a Reynolds number of 20×10^6, is approximately 70% of the theoretical value except at very low angles of attack. This agrees with results given in the early English literature, where experimental data at low Reynolds number showed a similar factor of 75 to 80% of the theory.

It appears reasonable that pitching and yawing moment data are less sensitive to Reynolds number since the moment is primarily determined by the pressure distribution on the forward part of the hull where agreement with inviscid theory is good.

Early investigators expended much effort on questions of fin effectiveness and fin loading, as these items had been identified as major sources of structural difficulty. In spite of this, no general predictive procedure emerged. Only a number of generalized statements can be made about the factors affecting fin characteristics.

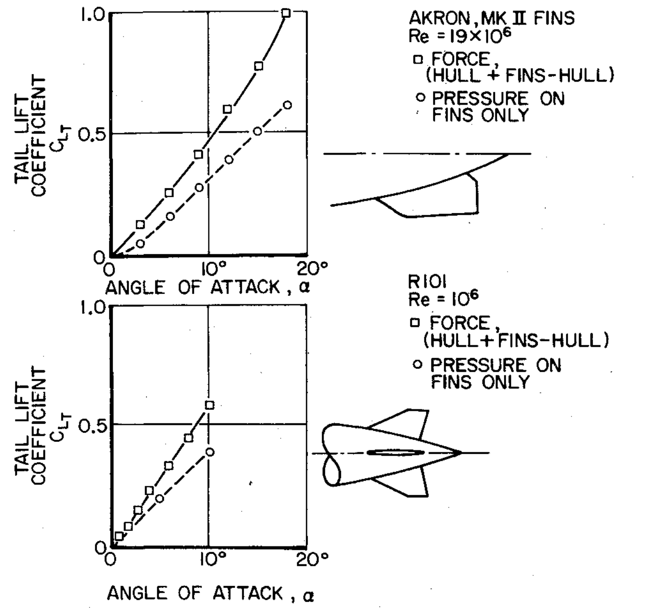

Fig. 8 Influence of "carry over" lift on tail lift coefficient.

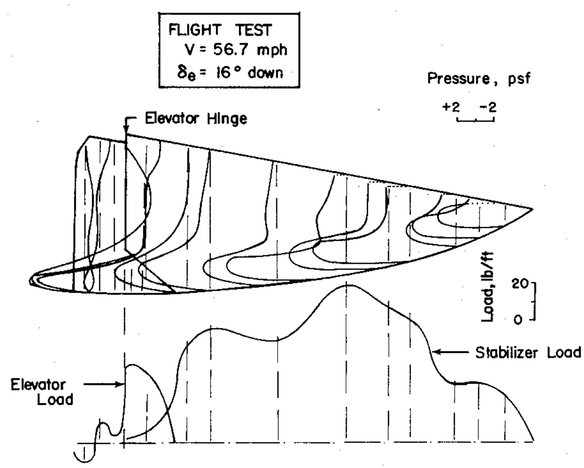

Fig. 9 Fin pressure distribution and loading measured in flight tests on the Los Angeles while flying through gusts.

As shown in Fig. 8,[16, 17, 25-27] perhaps the most striking characteristic of the hull-fin combination is the very strong "carry over" lift induced by the fins on the hull. Prandtl and Fuhrmann[2] noted as early as 1910 that fins on a hull produced 60% more force than the fins joined together. The extensive tests conducted on the Akron model[16] suggest a figure of 40%.

It is very difficult to describe, in detail, the flowfield in the vicinity of the fins. As previously noted, separated flow at the after end of the hull organizes into a set of body vortices as angle of attack increases. These vortices influence the flowfield at the fins. In addition, both, because of structural problems and because of the necessity of maintaining ground and hangar clearances, the fin planform typically was of low aspect ratio and highly swept. As a result, the fins generate leading-edge vortices. These vortices, taken with the wake vortices from the body, produce loadings which were difficult to interpret, and in at least one instance, fatal to the vehicle.[28] Fin loadings, measured in flight[29] and in a wind tunnel,[17] are presented in Figs. 9 and 10 illustrating the very strong influence of the leading-edge vortices on the pressure distribution.

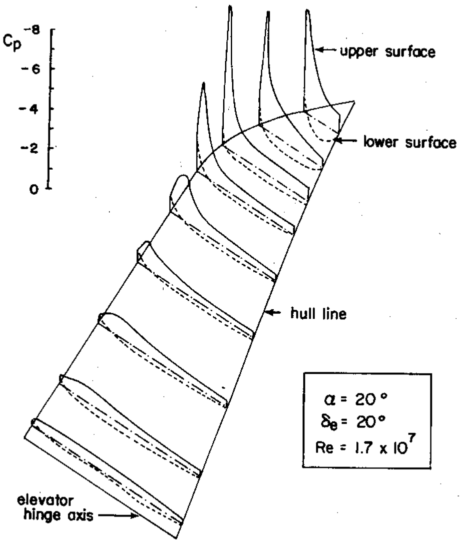

Fig. 10 Fin pressure distribution measured on 1/40 scale model of the Akron.

Control effectiveness is another area where data are both scarce and contradictory. In fairness, it should be pointed out that control surface design progressed substantially during the period over which these data were collected. Early tail surfaces frequently had separations between the fixed and movable portions of the fin of well over a foot.[8] Little or no attention was paid to the leading-edge shape of the control.

As a result, many of the early English results show significant nonlinearities in control effectiveness. For example, the yawing moment produced by rudder deflection at zero sideslip is considerably smaller than at an angle of sideslip.[8] Later NACA data, obtained from the large model of the Akron[16] show a reasonably linear relationship between moment and control deflection which is not strongly affected by sideslip angle.

There appear to have been few experiments conducted to determine the importance of interactions such as the effect of angle of attack on yaw control or vice versa, although at least one reference[2] states that the effects are small.

There is no question that the early designers were primarily concerned about structural strength and weight to the exclusion of almost everything else. The performance was so marginal that designers frequently turned a blind eye to the obvious and hoped for the best. Unfortunately, physics generally proved stronger than their faith. The accident report on the R 38 disaster contains some revealing statements[30]:

> "The design staff considered the aerodynamic stresses to be less important than the static stresses, although a few observations and calculations around a model airship were available which indicated very large bending moments.... The Committee was informed that calculations as to the aerodynamic forces had been made for the R 29 but that they showed so large a resultant bending moment that, in the opinion of the design staff, such a basis for the R 38 was precluded by considerations of weight...."

In order to resolve some of these questions, a number of full scale pressure distribution measurements were undertaken. One of the most ambitious investigations employed the R 33[31] and involved 200 pressure taps along the longitudinal axis of the hull, 100 taps on a fin, and 22,000 ft of manometer tubing. Other tests were conducted on the C-7 airship,[32] the Los Angeles,[29] and a number of others.[33]

Given the nature of the problem and the equipment available, it is not surprising that conclusions frequently read:[8] "...showed general distribution of pressure. The results, however, are practically useless in determining total forces."

Many of the references noted that gusts produced very large loads and would have to be considered in the design. Reference 32 summed it up succinctly: "It is concluded that the pressures set up by a bump are larger than those obtained in maneuvering."

Equilibrium Flight and Dynamic Stability

Owing to symmetry, the aerodynamic forces and moments acting on airships in pitch and heave are similar to those in yaw and sideslip. A very early examination of the stability of airships[34] points out the importance of considering the longitudinal motion as a two-degree-of-freedom problem. Because of aerostatic lift, the dynamic motion in pitch differs from that in yaw, and the trim requirements[35] are quite different about the two axes. However, since consideration of stability involves similar aerodynamic terms about either axis,[8] this discussion is restricted to equilibrium in turns and directional stability. The roll degree-of-freedom, although uncontrolled, lightly damped and probably annoying to the airship occupants, is weakly coupled to the directional motion[8,36] and therefore, will not be considered.

Generally, the English literature[8,36] contains a much more detailed examination of dynamic stability than that found in U.S. literature.[37] Thus, much of the following discussion is based on English results. Although there are complete sets of stability derivatives presented for a few airships,[8,25] there is little discussion of the significance of the time constants of the motion. The literature largely concentrates on stability and equilibrium in steady turns. It is interesting to note that popular accounts of airship history[38] tend to describe more difficult control problems than those indicated by the technical literature. Many of these difficulties are related to such factors as "sloshing" of the lifting gas, valve operation, and the delicate vertical equilibrium. The literature examined sheds little light on these questions.

The aerodynamic contributions to directional (or longitudinal) stability have one distinct feature: the nonlinear variation of the yawing moment (or pitching moment) and side force (or normal force) with sideslip previously discussed and shown in Fig. 7. All the experimental data examined indicate that the rate of change of side force with sideslip increases with sideslip angle and the rate of change of yawing moment with sideslip decreases as shown in Fig. 7. As a consequence, airships that are unstable in rectilinear flight become stable at some angle of sideslip,[8] that is, in a steady turn.

In rectilinear flight, the two-degree-of-freedom directional motion of some airships was unstable and others stable.[8,26,39,40] Conflicting information is found on the Los Angeles; full-scale turning data[41] and model data[4] indicate instability in rectilinear flight, but in Ref. 42 it is stated that "the course stability is very good". Note that in Ref. 4, the stability derivatives of the Los Angeles are estimated for a steady turn ($\beta = 5°$) and neutral stability is indicated. If these data are used to determine the stability derivatives in recilinear flight ($\beta = 0°$), unstable motion is indicated.

To obtain a complete description of the directional motion, the yaw rate derivatives must be evaluated as well as the sideslip derivatives. Airships do not possess weathercock stability ($N_\beta < 0$), however, when the two-degree-of-freedom problem is considered, this does not imply that the vehicle is dynamically unstable because of the effect of the yaw rate derivatives.

The variation of yawing moment with yaw rate was measured by free oscillation tests[25,26,43] on small models ($Re \cong 10^6$). Forced oscillation techniques were also employed[44] which showed good agreement with free oscillation results. Whirling arms[45] and curved models[4] were also tried. Oscillating model tests measure the sum of two derivatives

Table 2 Tail drag compared to bare hull drag

Airship	Bodensee[4]	R 29[8]	R 32[8]	R 33[8]	R 38[8]	Los Angeles[4]	Akron[16]
Fineness ratio	6.7	10.2	8.2	8.2	8.2	6.90	5.92
S^T_{wet}/S^H_{wet}	~.1	0.08	0.06	0.06	0.07	0.07	0.11
$\mathrm{Drag}^T/\mathrm{Drag}^H$	0.27	0.18	0.07	0.12	0.07	0.22	0.24
$\dfrac{\mathrm{Drag}^{T/H}}{S^{T/H}_{wet}}$	~2.7	2.2	1.2	2.0	1.0	3.1	2.2

Table 3 Effective tail lift curve slopes determined by various techniques

	$\bar{a}_{T_o}$		$\bar{a}_{T_{10}}$	$\bar{a}_{T_D}$	Aspect ratio $\dfrac{(\text{total span})^2}{\text{plan area}}$	$\bar{a}_T = \pi AR/2$
R29	.7		2.60	3.61	1.2	1.88
R33	1.83		2.96	3.19	0.70	1.10
R101	2.69		3.35	4.78	1.82	2.86
Los Angeles		1.34		3.62[a]	1.08	1.70

[a]Curved model.

$(N_r+N_{\dot\beta})$ and the derivative Y_r cannot be determined. In whirling arm and curved model tests, N_r and Y_r are directly measured. However, the interpretation and correction of whirling arm experiments for centrifugal effects and other factors is complex, and curved model tests require a different model for each yaw rate, so the majority of results were obtained from free oscillation tests. Generally, there are limited indications that results from all of these techniques were in agreement and that $N_{\dot\beta}$; is not significant; however, there is a lack of detailed information in this regard.

Experimental results indicated that the bare hull contribution to the yaw rate derivatives is small, and that the tail contribution is very significant. Usually, the tail contribution to Y_r was calculated from the measured tail contribution to N_r and an effective tail length, λ, determined from the ratio of N^T_β to Y^T_β.[8]

It is interesting to note that the damping measurements typically yield a much higher effective lift curve slope for the tail than found from sideslip data. This is indicated in Table 3 where an effective tail lift curve slope has been estimated from various experimental data. The nonlinear nature of the lift is shown by the difference in the slopes near zero and at 10°. Care should be taken generalizing these results since as late as 1937,[28] it was concluded that it was not possible to generalize the data on tail forces as a result of insufficient information.

Another question relating to dynamic stability is the estimation of the virtual mass terms.[10] These contributions are particularly important in determining the time scale of the dynamic response.

Although numerous flight tests were conducted to measure the dynamic response, the instrumentation was rudimentary, consisting, for example, of a sideslip vane suspended on a cable 75 ft below the hull, a compass or sundial, and a stopwatch.[41] Rate gyros of the era were not sufficiently sensitive to be of use.[41] Therefore, no flight data are available which give the time constants of the transient motion.

Linearization of the directional equations of motion about a steady turning condition was examined,[36] and it was found that the horizontal velocity coupled to the directional motion, influencing the characteristic roots to a small degree.[36] There are indications that the yaw rate derivatives depend upon sideslip[8,4]; however, this dependence does not appear large and can be neglected.

The equations of motion for the two-degree-of-freedom motion in yaw and sideslip may be written as follows[36] assuming the yaw rate effects are linear and the $N_{\dot\beta}=0$:

$$m_y V_o\dot\beta + m_x V_o r = Y(\beta,\delta_r) + \frac{\partial Y}{\partial r} r \tag{1a}$$

$$I\dot r = N(\beta,\delta_r) + \frac{\partial N}{\partial r} r \tag{1b}$$

Eliminating the yaw rate from these two equations gives a single differential equation which describes the stability of motion

$$m_y V_o\ddot\beta + \{-\frac{\partial Y}{\partial\beta} - \frac{1}{I}\frac{\partial N}{\partial r} m_y V_o\}\dot\beta + \frac{1}{I}\frac{\partial N}{\partial r} Y(\beta,\delta_r) + (m_x V_o - \frac{\partial Y}{\partial r})\frac{1}{I} N(\beta,\delta_r) = 0 \tag{2}$$

The last two terms in Eq. (2) are referred to as the effective restoring moment. A virtual mass contribution appears in the restoring moment through the term m_x, however, its influence is small for the fineness ratios typical of airships.[4] (Such contributions are significant in the determination of m_y and I,[4] and are important in determining the actual roots of the characteristic equation.[36] As an order of magnitude, $m_x \sim 1.1\,m$, $m_y \sim 2m$, $I \sim 2I_A$.) The stability of the airship is determined by the variation of the effective restoring moment with sideslip. A typical variation of this quantity with β and δ_r, for an unstable airship (R 29b) is shown in Fig. 11.[40] For zero rudder angle, the vehicle has three equilibrium conditions, rectilinear flight at $\beta = 0$ and steady turning at $\beta = \pm 2.4°$. The slope of the restoring moment with sideslip indicates that rectilinear flight equilibrium is unstable and that the curved flight equilibrium conditions are stable. At constant rudder angles of 5° and 10°, there is only one equilibrium point and the slope indicates stability. Thus, with zero rudder deflection, this airship would tend to fly in a steady turn. This characteristic has been verified by flight test.[40]

Figure 12 is an interesting example of a flight experiment. Rudder angle and heading are shown as a function of time during an attempt to fly an unstable airship (R 38) on a straight course for an extended period of time.[39] One can clearly see the nature of the steering problem. It may also be noted that as time elapsed, the inexperienced helmsman began to learn the dynamic behavior, and was able to reduce the deviation from the desired course.

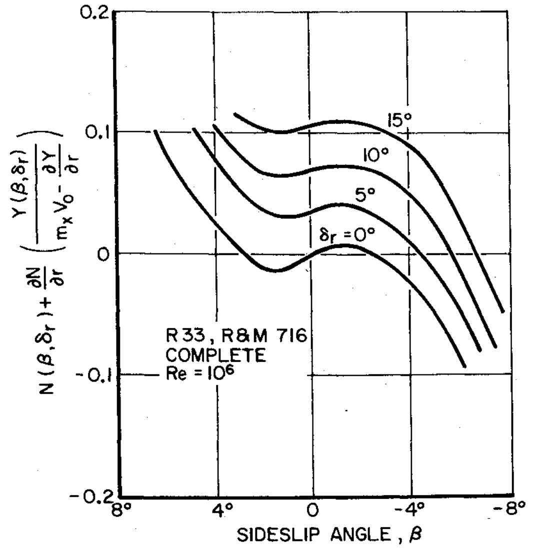

Fig. 11 Variation of effective restoring moment in yaw with sideslip angle and rudder deflection.

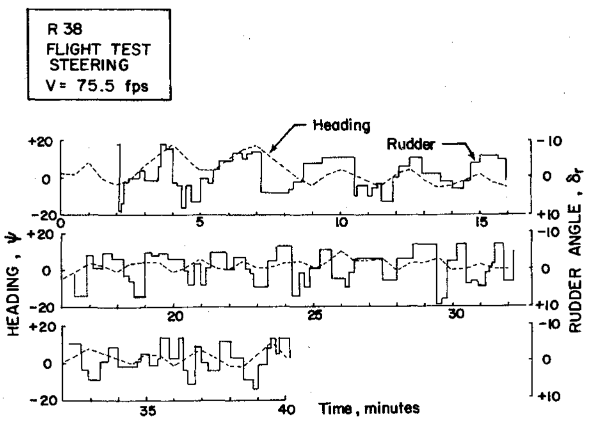

Fig. 12 Time history of directional steering of R 38 airship.

Flight test and model results for the relationship between sideslip and rudder angle in a steady turn for various stable and unstable airships are shown in Fig. 13.[8, 25, 41] Generally there appears to be excellent correlation between model and flight test in the case of the R 38. Similar agreement is shown for other English airships.[8] The turn radius is approximately related to the sideslip angle by the equation $R\beta = \lambda$.[8]

Although some attempt was made to define criteria for stability and controllability,[8] desired levels of stability and control do not seem clear. Given the fact that $R\beta$ is approximately the same for various airships, then Fig. 13 shows clearly the tradeoff between stability and controllability. The R 29 which was probably stable in rectilinear flight, had one-half the turning capability of the R 29b which was distinctly unstable.[39] The R 29 could be steered on a straight course with somewhat less variation in heading than shown in Fig. 12 using only $\pm$ 2° of rudder deflection.

A summary of the full scale characteristics of the various airships dicussed can be found in Ref. 21.

Search of the literature to date relating to the stability and control of airships has failed to disclose treatment of a number of topics that it appears would have been of considerable interest. Limited information on the question of gust response has been uncovered.[28] The cross coupling between controls and incidence (e.g., the effect of angle of attack on yaw control) does not appear to have been examined. There are statements to the effect that such coupling is small,[2] but no substantiating data have been found.

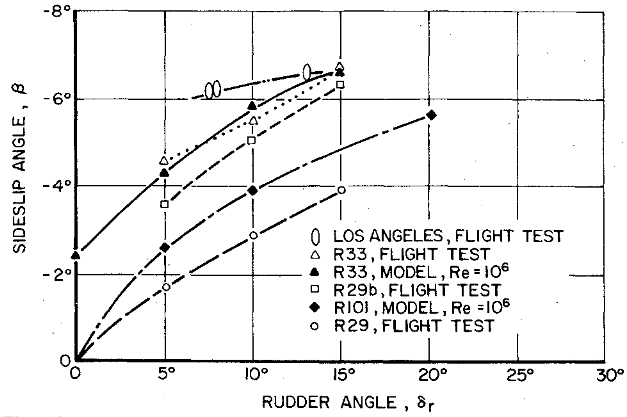

Fig. 13 Steady state turning characteristics; sideslip angle as a function of rudder angle.

Further questions on which little or no information has been found relate to handling and ride qualities of airships other than considerations of steering a straight course and the roll dynamics. The roll dynamics do not appreciably affect the control problem; however, it might be expected that the small roll damping would lead to uncomfortable motions in gusts.

Finally, in an era before the function of the man in the control loop was understood, it is probably not surprising that the question of one or two helmsmen was not addressed, nor was the significance of the time constants of the airship and its control system in relation to the control task considered. The R 101 was equipped with servo controlled surfaces providing a maximum control deflection rate of 1° per sec.[46] There are no indications as to whether this control rate was adequate, as well as no discussion of criteria for control rate response.

Summary

It has not been the purpose of this survey to reproduce in summary form the data presented in the bibliography. Rather, the attempt has been made to identify areas in which the existing data may be used with fair confidence; those in which less confidence is warranted; and those where little or no data exist.

It appears that modern methods of drag prediction, based on improved understanding of boundary-layer phenomena, will provide a zero dynamic lift drag prediction of greater reliability than much of the published data.

Force and moment data of hulls with and without fins can be approximated for most purposes with fair reliability from a judicious application of potential flow theory modified by empirical data. Similar conclusions can be drawn about turning characteristics.

The problem of estimating stability derivatives is in less satisfactory condition, primarily because the experimental data were obtained on small models at low Reynolds numbers, and the precision of flight test techniques and instrumentation of the time were inadequate to the task of providing full-scale verification. In the areas of response rates, coupling effects, and controllability, there are very few data extant to employ for experimental verification of modern analytical techniques.

Whether or not such experimental verification will be forthcoming in the future will depend upon the degree to which the application of the existing body of information can build a convincing case that LTA vehicles can perform the desired missions in a reliable and cost-effective manner. It will be a chicken and egg process. We must use what is available to obtain the vehicles necessary to measure the remaining unknowns. Based on the revisit of the data conducted herein, and given an adequate degree of skepticism translated into over-designed capability, there seems to be no area of such overriding uncertainty as to preclude proceeding with full-scale design should tradeoff studies prove this to be desirable.

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