Application of Advanced Methods to Design Loads Determination for the L-1011 Transport

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An over-all view is presented of the approaches used to obtain design loads for the Lockheed L-1011 TriStar transport. A coordinated effort involving many engineering disciplines was required. Loads were obtained as panel loads, using two and three dimensional grid systems. Aerodynamic force distributions were based on lifting surface theory and on pressure data obtained from wind tunnel model tests. Extensive use was made of matrix concepts and matrix algebra both in data handling and in solving the aeroelasticity equations to obtain panel load distributions. Scanning procedures were developed to weed out noncritical conditions. Loads and spectra for fatigue analysis and test were obtained by the same methods used to obtain limit load conditions. The methods of loads analysis were validated by means of various test programs, including extensive flight and ground loads measurements on an instrumented airplane.

Introduction

THIS paper presents an over-all view of the procedures of establishing design loads for a modern jet transport. Specifically, it describes the external loads determination for the Lockheed L-1011 TriStar, with emphasis on those procedures considered relatively advanced. The general approach and some of the specific static loads procedures are covered herein; a companion paper, Ref. 1, describes the determination of the dynamic loads conditions.

The primary responsibility for establishing structural design criteria and external design loads for Lockheed-California Co. commercial transport aircraft lies with the Commercial Engineering Loads Dept. In fulfilling this responsibility, the objective is to define criteria, loads, and repeated loads spectra that will lead to a safe, troublefree, and economical structural design. The resulting level of structural integrity must be compatible with the anticipated operational environment, both normal and extreme, encompassing maneuvering flight, flight in turbulence, landing, taxi, and ground handling, including the effects of possible system failures.

FAR 25 defines the minimum U.S. structural requirements for commercial airplanes. For the L-1011, these were supplemented by a number of FAA Special Conditions. Since British certification was also desired, the L-1011 also had to meet requirements negotiated with the ARB (Air Registration Board). It was necessary that these formal requirements be interpreted, expanded upon, added to, and carefully implemented, in order to achieve the desired structural integrity.

Table 1 presents a summary of the types of condition that were investigated. These were investigated for all combinations of possible configuration (as defined by flap extension, spoiler deployment, and landing gears up or down), speed, altitude, gross weight, center of gravity, fuel and payload quantity, and payload distribution. Although Table 1 applies specifically to limit (or ultimate) design loads, the general scope indicates the coverage given to repeated loads spectra as well. Not included in Table 1 are a number of additional structural sizing considerations such as sonic environment, vibration control, and flutter prevention, which are outside the intended scope of this paper.

The process of design loads determination can be considered to fall into five phases: 1) advance testing, 2) preparation, 3) loads generation, 4) scanning and stacking, and 5) validation testing. These phases—especially phases, 2, 3, and 4—are repeated through several overlapping cycles as the design progresses, as progressively more complete and accurate data become available, and as refinements are made in the methods of analysis.

Panel Loads and Matrix Algebra Approach

A feature common to both loads and stress analysis of the L-1011 primary structure was the two and three dimensional nature of the analyses and, as a result, the use of two and three dimensional grid systems. In the past, for airplanes having high-aspect-ratio straight and moderately swept wings, the stress analysis could be performed by means of simple beam theory. The design loads could be presented as shears, bending moments, and torsions, and wing stiffness data as spanwise variations of EI and GJ. Major parts of the L-1011 structure, however, could be ana-

Table 1 Classification of major primary-structure design conditions

I. Flight maneuvers—pilot-induced and due to airplane system malfunctions
   1) Pitch maneuvers—steady and transient
   2) Roll maneuvers—steady and transient
   3) Rudder maneuvers
   4) Combinations of 1,2 and 3
   5) Engine failure

II. Flight in atmospheric turbulence
   1) Power-spectral approach—"mission analysis" and "design envelope" criteria
   2) Static loads per FAR gust load factor formula
   3) Tuned discrete gust dynamic loads (one-minus-cosine shape with varying wave length) for British certification

III. Landing
   1) FAR landing conditions (gear and static airframe conditions)
   2) Dynamic landing conditions (obtained from elastic mode time history analyses using FAR-specified sink speeds, wing lifts, etc.)

IV. Ground handling
   1) FAR ground handling (braking, unsymmetrical braking, turning, pivoting, towing)
   2) Rational taxi conditions (bump encounter during take-off runs, rejected take-offs, landing runout, taxiway taxiing)
   3) Rational turning and braking
   4) Jacking

V. Failsafe and breakaway design

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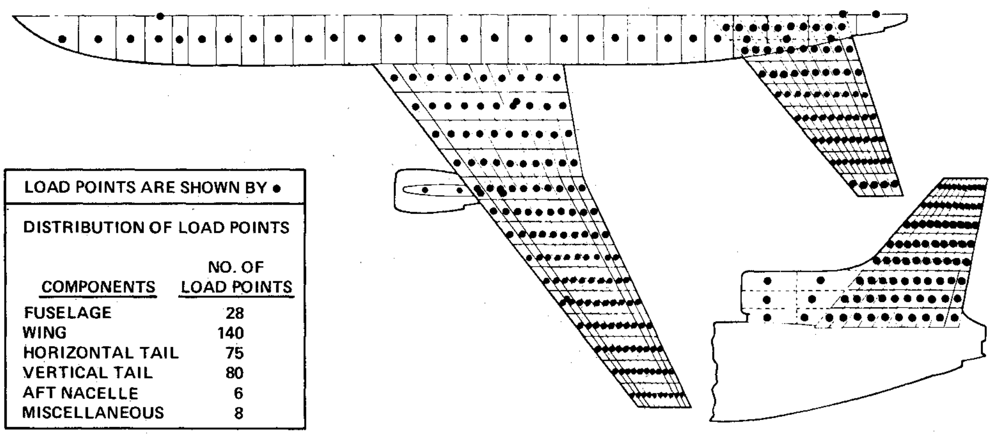

Fig. 1 Basic loads grid system.

lyzed properly only by resorting to the finite-element redundant-structure "model," or idealization, described in Ref. 2. Use of this stress model required the loads inputs to be defined on a grid, or panel loads, basis. Furthermore, the methods of loads determination considered necessary for use in the design of the L-1011 involved lifting surface theory and extensive wind tunnel pressure surveys. Consequently, these methods, too, required a two or three dimensional approach. Design loads, therefore, were readily available in the grid system format required by the stress analysis. Methods of both loads determination and stress analysis meeting these requirements had been developed during the 1963–1966 period for application to the Lockheed SST, which because of its low-aspect-ratio delta wing could be analyzed in no other way. The methods were available, therefore, together with personnel familiar with their use, at the start of the L-1011 development program.

A number of different grid systems were found necessary to accommodate the various analyses. These consisted of the following:

1) Kernel function control point grid. This grid defines the collocation points used in the lifting surface theory. The theoretical airloads over the airplane are expressed as functions of angle of attack at these points. This grid was required by the available theory to be laid out at prescribed constant fractions of chord and semispan.

2) Basic loads grid (337 points per side). This grid was used at various stages in the loads generation process. Its major features are shown in Fig. 1. The panels were made small enough to provide good accuracy in both airload and weight distribution. On the lifting surfaces, the panel boundaries were laid out streamwise and at constant fractions of chord so that pressures given by the lifting surface theory could be integrated in closed form to give panel airloads. All weight data were provided on this grid, and design-condition panel loads were first defined on this grid prior to transformation to the SIC grid for use in stress analysis.

3) SIC grid (197 points, 333 load/deflection components, per side). This is the grid on which structural (deflection) influence coefficients were provided for use in loads analysis and on which external panel loads were defined and provided on computer tapes as inputs to the stress model. It was laid out to best define the deflection characteristics of the structure. It was generally somewhat coarser than the basic loads grid.

4) Various grids obtained by selecting points from the SIC grid, used as coordinates in various loads analyses (usually 90–160 load/deflection components).

5) Grids defining orifice locations on the wind tunnel pressure models.

A feature of both the loads and stress analyses closely related to the use of grid systems was the extensive use of matrix algebra. This was facilitated by a library of matrix manipulation computer programs called FAMAS (Flutter and Matrix Algebra System). FAMAS readily handled the conventional matrix algebra operations such as matrix addition, multiplication, inversion, and eigenvalue and eigenvector solutions. It was also able to perform other very useful operations, not consistent with formal matrix algebra, such as element-by-element multiplication and division. The FAMAS system was used to carry out the closed-form aeroelastic solutions in which panel loads were defined over the entire airplane for the various maneuver conditions. It was also used to generate elastic vibration modes and related input data used in the dynamic loads analyses and in the final processing of dynamic loads data into panel loads form.

Some of the matrices that reflected basically geometrical data and were used repeatedly in the loads analysis were the following:

1) Grid transformation matrices which when multiplied by panel loads or deflections in one grid yield loads or deflections in another.

2) Load integration matrices which when multiplied by panel loads in a given grid system yield load quantities such as shears, bending moments, torsions, hinge moments, empennage loads, etc. Although the L-1011 design loads were defined basically in panel loads form, extensive use was made of computer plots of shears, bending moments, and torsions to give visibility to the analysis.

3) Differentiating matrices which when multiplied by structural deflections yield angles of attack at aerodynamic collocation points.

4) The alpha (angle-of-attack) distribution due to airplane camber and twist at the aerodynamic collocation points.

5) "Alpha-delta" and "beta-delta" distributions which define the effective angle of attack at each aerodynamic collocation point due to unit deflections of control surfaces (stabilizer, elevators, ailerons, rudder, spoilers, flaps, and slats).

6) A series of interpolation, integration, and sweeping matrices used in processing the wind tunnel pressure data.

These matrices generally reflected fairly simple concepts. For example, transformation of loads from a fine to a coarser grid was based on "beaming" to the coarse-grid points. Transformation of deflections from a coarse to a fine grid was likewise based on an assumed beam network and was equivalent to a system of linear interpolation. Integration of panel loads to give shears, moments, and torsions involved simple summing of loads or loads times moment arms (with special treatment given to panels cut by the section at which the shears, moments, and torsions were obtained). In some instances, the generation of these matrices could be systematized and mechanized; in others, it was necessary to generate each element individually.

The panel loads and matrix algebra approach was found to be practical even in the fairly early stages of design. During the preliminary design stage, smaller-order grid systems were set up for many configurations. Loads calculations were performed by the same general methods used later, although the input data lacked the refinement and verification available later in the program.

The panel loads approach was very useful in transmitting data to the stress and test organizations. Computer tapes of external panel loads were fed directly into finite element structural stress models to obtain internal loads. In the case of the wing and empennage, these tapes were transmitted by air from Burbank, Calif. to the Lockheed facility at Marietta, Georgia, where those components were being designed.

Data Requirements

Extensive airplane data of various types is vital to accurate loads determination. The data needed can be categorized as airplane geometry, aerodynamic data, stiffness data, weight data, systems data, and operational data. The sources of the data in several of these categories are discussed in detail below. The major data flow paths related to the loads determination, along with the associated organization interfaces, are summarized in Fig. 2. The feedback effects of structural sizing, both on the internal load distribution and on the external loads themselves, can be traced in the lower right-hand part of the figure.

Aerodynamic Data

The recent trend toward using lifting surface theory in representing the entire airplane in an analytical aerodynamic model, in which the flowfield interaction between, as well as within, major airplane components is represented, has made available a powerful and useful analytical tool. The aerodynamic data from such a model is ordinarily provided and used in the form of aerodynamic influence coefficient matrices (AIC's), in which the rows represent the panels at which loads are to be calculated and the columns represent points at which angles of attack are defined. Thus postmultiplying the rectangular AIC matrix by a column matrix containing the angles of attack yields the panel airloads.

In the design of the L-1011, lifting surface theory was used in conjunction with extensive pressure data obtained from wind tunnel pressure model tests as well as wind tunnel force data. In generating the symmetric flight maneuver loads conditions, the pressure data was used directly to give the part of the airload distribution associated with a rigid airplane at a constant angle of attack, while the lifting surface theory was used to determine the incremental airloads due to elastic deformation of the structure and also those associated with pitch velocity. In generating the lateral-directional maneuver conditions, instead of using the pressure data directly, the AIC matrices provided by the lifting surface theory were adjusted so as to match the pressure data as closely as possible. This match, of course, could be made only for the special case of a constant angle of sideslip over the entire airplane. The adjustments were made panel by panel, by multiplying each row of the AIC matrix by the ratio of test to theoretical values of the aerodynamic force on the associated panel. In addition, both symmetric and antisymmetric AIC matrices were adjusted to reflect wind tunnel force data; these adjustments generally involved a constant factor applied over each of the major airplane components. In order to match force and pressure data associated with control surface deflections, it was sometimes expedient to alter the "alpha-delta" and "beta-delta" matrices rather than the AIC matrices.

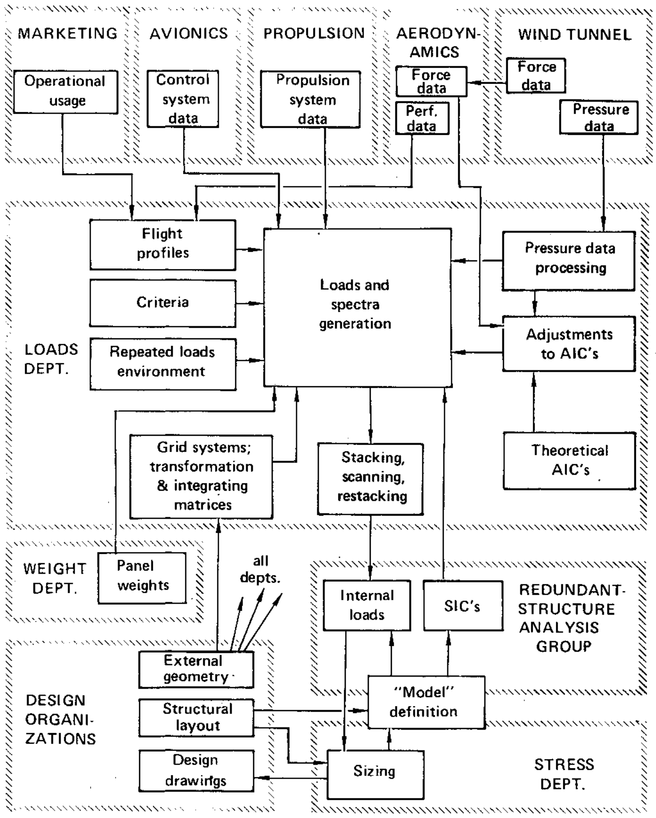

Fig. 2 Major data flow paths involved in L-1011 loads determination.

Prior to the availability of the pressure data, lifting surface theory was used without correction to define preliminary loads. The lifting surface theory was also used to account for the effects of late configuration changes not included in the wind tunnel models.

Kernel Function Lifting Surface Theory

The major theoretical tool used to establish airload distributions for the L-1011 was the kernel function procedure of NASA TR R-48.[3] The original program was obtained from NASA in 1960 and was extensively modified and improved at Lockheed during the middle and late 1960–1970 time period. Collocation point limits were expanded from 16 to 100/half airplane/lifting surface. Integrations were added which computed the individual pressures, lifts, and moments on any number of selected panels on the surface. These were "closed form" integrations, which integrated directly the trigonometric functions (modes) inherent in the method of TR R-48; the only restriction was that the panels had to be bounded by constant fractions of span and chord (Fig. 1). In addition to the basic over-all integrated force data, such as lift curve slope, pitching and rolling moment coefficients, and section data, the output of the program as modified included aerodynamic influence coefficient matrices. In the AIC matrices provided by the program, the number of columns was limited to 100 collocation points/side/surface; there was no limit, however, on the number of panels at which forces could be defined. The program was extended further to include the option of calculating flowfield away from the lifting surfaces, in terms of vertical, lateral, and longitudinal components of velocity as a function of change in angle of attack of each collocation point. It was relatively simple, by use of matrix partitioning and building-block techniques, to formulate one AIC matrix representing the aerodynamics of the entire airplane, including the interaction of the tail and wing, the upwash on the

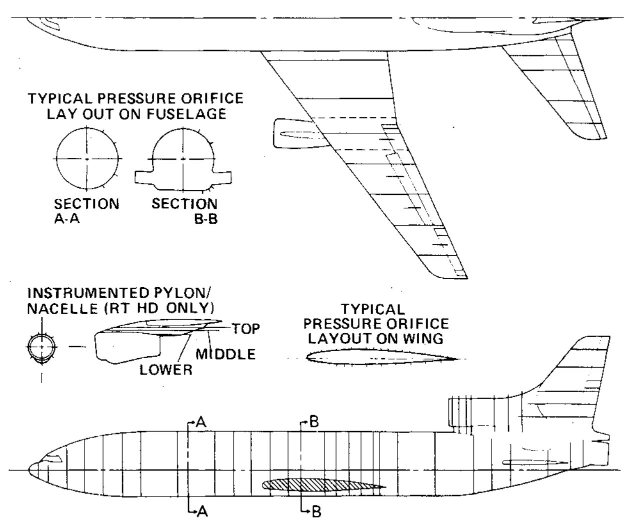

Fig. 3 Pressure orifice locations on high-speed pressure model.

nacelles and fuselage, and also ground effects where appropriate. Slender body theory was used for the fuselage forebody, with the effect of upwash from the wing included. The building block technique permitted careful monitoring of individual surface characteristics, such as wing and horizontal tail lift curve slopes and downwash at the tail, against wind tunnel force data. The indicated adjustments could then be made readily, either in the AIC matrices as stored for general use or as part of the loads generation computer runs.

On the basis of comparison with the wind tunnel pressure data, the lifting surface theory was found generally to give excellent results for the clean configuration up to a Mach number of $M = 0.8$ and angles of attack of 6°, except for the magnitude of fuselage wing airload carryover. At higher Mach numbers, lifting surface theory alone considerably underpredicted the aft shift in local section aerodynamic center due to shock formation and thus underpredicted design wing loads. Obviously this type of theory will not predict transonic shock flow effects and nonlinear effects in the stall region; however, for those regions where linear potential flow theory would be expected to apply—with the single exception of the lift carryover to the fuselage—excellent correlation was found. This was seen in such items as lift curve slope, aerodynamic center, zero lift angle and pitching moment, aileron hinge moment, and even airload distribution. This good correlation was consistent with results obtained earlier for the Lockheed SST, except for the virtual absence of transonic effects on the SST because of its very high leading edge sweep and slender fuselage.

Although the primary application of the kernel function theory in the L-1011 loads generation involved only the steady state, or zero frequency, solutions, the theory of Ref. 3 also provides for oscillatory solutions. These were used on a limited basis in connection with the dynamic gust analysis, as discussed in Ref. 1. For this purpose, the adjustments indicated by the pressure data at zero frequency were assumed to apply also at the higher frequencies.

Vortex Lattice and Doublet Lattice Lifting Surface Theories

In addition to the kernel function technique, which in broad terms could be classified as a distributed function technique for solving the lift potential flow equation, a discrete vortex lattice technique, similar to that of Ref. 4, was also used for certain applications. This method is in many ways easier to visualize since the airplane is represented by a series of panels each of which contains a horseshoe vortex at its quarter chord. Panels are represented not only on the lifting surfaces but also on the fuselage surface, pylon and engines. The strengths of the individual vortices are determined by solving the simultaneous equations to satisfy the boundary condition of no flow normal to the surface at the three-quarter-chord-point of each panel. This program was used only on a zero frequency basis. It predicted the fuselage-wing carryover effects and nacelle-induced effects on the wing more accurately than the kernel function technique but still not accurately enough for use in place of pressure model data. One advantage of this program was that it did not require a building block technique, in that the entire airplane could be represented in one run. The program was used in studies of induction effects in the aftbody-empennage section of the L-1011, where the geometry was complicated by the S duct and wide fuselage in close proximity to the horizontal and vertical tails. Pressure model data was used to define the rigid-airplane loads in this area, and the vortex lattice method was used to predict the incremental airloads due to structural deflection including the induction effects. Recent work at Lockheed using a doublet lattice approach, similar to that of Ref. 5, has also shown considerable promise, not only for the zero frequency solution but also for nonsteady solutions.

One disadvantage of both the doublet and vortex lattice approaches is the large number of equations to be solved when a fine enough lattice is used to give the required accuracy. Whether an over-all increase in computing time would result, however, has not been clearly established.

Wind Tunnel Pressure Model Tests

A series of wind tunnel pressure model tests was run specifically to support the loads analysis in establishing accurate airload distributions over the entire airplane. Two models were constructed—a 1/30 scale model (wing span 5.2 ft) to measure high speed characteristics (Mach range 0.5 to 0.98) for the basic and high drag configurations, and a 1/20 scale model to measure low speed characteristics for all configurations including the various flaps-extended configurations. Tables 2 and 3 summarize the tests run with these two models. Figure 3 illustrates the general location of the orifices for the high speed model.

Test N134 provided the basis for preliminary loads. In this test, the number of orifices was limited to five spanwise stations on the wing and 12 stations on the fuselage. The integrations of the pressures on the wing were facilitated by using kernel function modes to establish analytical surface pressures that faired through the pressure data

Table 2 Wind-tunnel pressure tests—high-speed model (basic and high-drag configurations)

Test no.	Tunnel	Date	Tunnel hr	Orifices	Type of test
N131	Cornell	12/30/67	20	241	Preliminary–early configuration
N134	Cornell	1/30/68	25	305	Preliminary–final configuration
N160	Cornell	6/8/68	150	916	Sting mount
N167	Cornell	7/24/68	85	950	Blade mount–flow-through S duct
N176	Ames	8/15/68	80	222 (wing)	High Reynolds no.–sting mount
N248	Cornell	9/15/69	50	916	Sting mount–ice shape tests

and satisfied the surface edge conditions inherent in the modes. The integrations built into the theoretical kernel program were then used to calculate panel airloads. This technique was also initially used on tests N160 and N167 until a series of more exact integrations was developed.

A key challenge involved in the pressure model analysis was to reduce the very large quantity of data (5 million measured pressures on the high speed model alone) in a timely manner such that these data could be reflected in the design loads in phase with manufacturing and delivery requirements. Rapid and accurate data handling in time to meet production schedules is a very real practical consideration which has discouraged the use of models such as these on many past airplanes. Much detailed planning went into the data management. Negotiations were conducted well in advance with the test organizations and the computer programming groups, to insure that the computer tapes from the test facility could be fed directly into compatible data reduction programs at the Burbank computer facilities without the need for human data handling.

The basic steps involved in reducing the data consisted of the following: 1) data recorded at the wind tunnel on computer magnetic tapes in prearranged formats; 2) raw data in the form of pressure coefficients vs x/c plotted electronically on photo plots, stored on microfilm; 3) raw data converted to matrix form by computer; 4) data computer-scanned for bad points, data also visually scanned for bad points on a sampling basis; 5) bad values eliminated (swept) and corrected values inserted based on interpolating nearby good points; 6) data integrated into meaningful forms by computer and automatically plotted (e.g., section lift and moment data, spanwise running lift, spanwise and chordwise centers of pressure, total lift and moment on major components, etc.); meaningful forms visually inspected as a check that all bad points have been identified; integrated data correlated with independently measured force data; 7) data converted to panel load format; 8) final check of converted data by integrating panel format data into the same meaningful forms as step 6.

Matrices of panel loads at each measured angle of attack were stored directly in the pitch maneuver loads programs. For the purpose of adjusting the theoretical antisymmetric AIC matrices, pressure coefficient differences over an appropriate range of β were obtained panel by panel, for comparison with values calculated from the AIC matrices.

The data from the wind tunnel tests provided a very accurate knowledge of local airplane aerodynamic characteristics. Eight components of the high speed model were isolated for inspection; these were the wing, fuselage, horizontal stabilizer, vertical stabilizer, wing pylon and nacelle, S duct, rudder, and elevator. (The aileron and spoiler hinge moments were measured with strain gages and verified by pressure integrations.) Eleven components were isolated for the more complex low speed model.

Table 3 Wind-tunnel pressure tests—low-speed model (flaps-extended, basic, and high-drag configurations)

Test no.	Tunnel	Date	Tunnel hr	Orifices	Type of tests
L235	Lockheed	10/1/68	800	1,312	Fork and sting mounts
N210	Ames	11/4/68	80	794	High Reynolds no.
L235 II	Lockheed	2/3/69	200	1,390 (approx.)	Leading edge configuration change
L235 III	Lockheed	3/10/69	100	1,390 (approx.)	Flap system configuration change

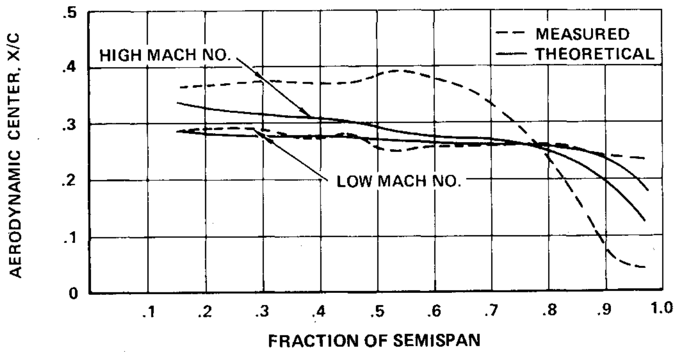

Fig. 4 Comparison of wing aerodynamic center given by lifting surface theory and wind tunnel pressure data at low angles of attack.

The impact of the pressure data on the loads was substantial. The wing spanwise variation of section aerodynamic center differed considerably from theory in the transonic region (Fig. 4). The lift carryover onto the fuselage from the wing was significantly less than indicated by wing-alone theory; while the fuselage forebody developed substantial lift in its own right, the lift on the mid portion of the fuselage due to the presence of the wing was less than indicated by the theory by 30% at low Mach numbers and 15% at the higher Mach numbers. (Later work using the vortex lattice theory, including representation of the body, indicated reductions of 50% and 15%, respectively.) The airloads on the vertical and horizontal stabilizer differed considerably from the values that would have been estimated by using the difference between airplane and airplane-less-tail wind tunnel force data as has been customary on many past airplanes. In particular, only 65% to 70% of the airload increment due to addition of the vertical tail, in sideslip, was found to occur on the vertical tail itself. Similarly, about 80% of the airload increment due to a change in horizontal stabilizer angle was found to occur on the stabilizer.

Stiffness Data

The stiffness data was provided in the form of structural (deflection) influence coefficients (SIC's), in terms of deflections per unit load. These SIC's were obtained by means of the finite-element redundant-structure model, described in Ref. 2. This model evolved from a simple two-dimensional representation through stages of various hybrid models and finally to the three-dimensional stress model.

Weight Data

The airplane weight data for each condition was provided in panel weight form, for prescribed values of operational empty weight (normal or check flight), payload, fuel weight, and airplane c.g. location. Payload was distributed in accordance with criteria involving reasonable combinations of uniform and block loading. Fuel weight was distributed in accordance with the design fuel management. The wing tank configuration and fuel management were planned to achieve operational simplicity and maintain fuel outboard through much of the flight, thus relieving the design wing loads for maneuvering flight as well as the one-g flight loads. Effects of fuel movement due to airplane fore-aft load factor (in effect, pitch attitude) and structural deflections were considered in the critical steady maneuver conditions, such as 2.5g steady turns, where a small increase in loads resulted. The program of Ref. 6 was used to establish accurate locations of fuel in the tanks.

Systems Data

The design and development of a safe and economical commercial transport requires the integration of structural design with the systems incorporated in the airplane. Systems which can strongly interact with the primary structure include the following: propulsion, primary flight control, automatic flight control, environmental control, fuel, hydraulic, and brake antiskid systems.

Knowledge of not only the normal operating characteristics but also the failure modes and effects of system malfunction are required in order to assure the desired level of over-all system/airframe integrity.

The magnitude of this task can perhaps be best appreciated by partial listing of the necessary data exchanges and coordinated analyses and tests required for the propulsion system alone on the L-1011. These included: net thrust, gross thrust, thrust distribution, engine mass data, engine deflection data and tests, engine vibration data, sonic environment (near field), bleed air pressures and temperatures, thrust reverser system safety characteristics, design loads and loads spectra for the engine (as installed in the L-1011), fan blade containment analyses and tests, bird ingestion criteria and tests, and asymmetric thrust due to inadvertent thrust reverser deployment in flight.

Primary flight control system characteristics of which knowledge was needed in order to determine primary airframe loads included rates under various loads, available hinge moments and surface travel, and mechanical advantages. Many of these characteristics varied with flight condition. The rudder system, for example, was designed to preclude extreme airplane excursions and high structural loads (and thus save structural weight) by changing from three hydraulic systems to one above speeds of 164 knots, and by reducing system pressure still further above 260 knots. In addition, a rudder mechanical limiter was installed to limit the rudder travel for the clean configuration above speeds of 164 knots. These provisions gave the pilot ample rudder operational capability at all speeds and yet insured that inadvertent rudder kicks (due to pilot error or combinations of improbable system failures) would not impose high structural loads on the airplane.

Potential system failure characteristics had to be identified, both electrical and mechanical. One of the FAA Special Conditions was that the airplane be capable of continued safe flight and landing following any combination of failures not shown to be extremely improbable (excluding jamming, which was treated separately). These included dual electrical or hydraulic failures and any single structural failure in combination with any probable hydraulic or electrical failure. Many of these combined failure cases required the development of special loading conditions for structural design. An entire analysis was performed to determine the effects on structural loads of possible Avionic Flight Control System (AFCS) failures, in particular those that would lead to trim runaways, control surface hardovers, and control surface oscillatory motions.

Loads Generation

It is convenient to describe the loads generation procedures in two categories—static aeroelastic loads and dynamic loads. Static aeroelastic loads involve types of load condition that, basically, can be calculated using D'Alembert's principle, in that aerodynamic forces are placed in equilibrium with rigid-body inertia forces. Dynamic loads, in contrast, are considered to be those in which the inertia forces associated with accelerations in the elastic modes contribute significantly to the loads. Dynamic loads calculations usually involve energy equations such as Lagrange's equations. In addition, loads dependent upon the dynamics of landing gear stroking, such as the landing-impact loads used for landing gear design, are considered to fall in in the dynamic loads category.

The static aeroelastic loads determination is discussed in the following section. The dynamic loads approaches used on the L-1011 call for a more detailed treatment, which is given in Ref. 1.

It may be helpful to observe that the loads generation phase for many of the conditions analyzed consists of two distinct sequential steps usually conducted using different computer programs and even different computer equipment. The first analysis—necessary for all of the dynamic loads conditions and for the transient maneuver static aeroelastic loads conditions—solves the airplane equations of motion for prescribed forcing functions and identifies potentially critical loads conditions. The forcing functions consist of such items as rapid control surface displacements, engine failure time histories, gear loads due to landing impact, runway profiles, and gusts of prescribed shape or power spectral density. The solving of differential equations that express airplane motion in response to discrete and random disturbances is a problem shared by many disciplines within an aircraft company—loads, aerodynamic stability and control, avionics, and others. The loads problem, however, is to determine not only the airplane motions but also key loads on selected parts of the airplane, from which to establish potentially critical conditions. Once these are established, the second step in the loads generation phase—necessary for all types of condition without exception—is to obtain for each condition the individual panel loads over the entire airplane.

Static Aeroelastic Loads

Panel Loads Computer Programs

Of the two sequential steps noted above as comprising the loads generation phase, the panel loads step is common to all of the static aeroelastic loads conditions and will be discussed first. Five distinct computer programs were developed, to provide for the various types of condition listed in Table 1. These will be discussed separately, although for certain types of condition two were linked together in the computer. The programs used stored matrices of basic data, calling these out by a few simple coded instructions. For all except the ground loads conditions, in which no air loads acted, the airload redistribution due to structural deformation was accounted for. The solutions were obtained in closed form and involved matrix inversions of 150th to 160th order. The programs consisted of the following:

1) Steady symmetric-flight pitch-maneuver program. This program computes the loads for steady pitch conditions. Angle of attack and stabilizer angle are treated as variables, with the program calculating the values required to give the desired load factor together with zero pitch acceleration. (Pitch control of the L-1011 is achieved by pivoting the entire stabilizer; the elevator is geared to the stabilizer to augment the stabilizer lift at large airplane-nose-up stabilizer angles.) Inputs include a number of "measured to theoretical" ratios which are used to adjust the over-all level of certain of the theoretical distributions, such as drag, to values indicated by wind tunnel measurement. The program calculates the more critical values of pitch velocity associated with either a steady turn, steady pull-up, or steady push-over. Types of condition investigated include: a) steady pitch maneuvers at specified points on the design maneuver envelope (V-n diagram); b) the symmetric part of FAR-required roll maneuvers (0 and 1.67 g); and c) 1-g loads for combination

with the appropriate incremental loads to form net loads for yaw maneuver, vertical gust, lateral gust, and landing conditions and for use in fatigue analysis. In addition, 1-g loads were determined for typical mid-cruise flight in order to establish an airplane "jig" shape (for manufacturing purposes) such that under 1g cruise conditions the airplane would deflect structurally to the optimum performance shape reflected in the wind tunnel models.

2) Transient symmetric pitch maneuver program. This program computes the incremental loads (from a steady 1g flight condition) during a transient maneuver. The angle of attack and pitch acceleration are treated as variables; the program calculates the values necessary to give the desired load factor and balance the calculated aerodynamic pitching moment. The values of these quantities given by the program are checked against those obtained as outputs of the time history analysis. Conditions run include incremental loads (from 1g flight) for a stabilizer maneuver and incremental loads (from 1g flight) for a quasisteady up or down gust.

3) Lateral Maneuver Program. Used primarily for wing design, this program represents purely roll motion based on a one-degree-of-freedom time history analysis. It outputs antisymmetric loads, such that the airloads due to aileron deflection, roll velocity, and structural deflection, together with the inertia loads due to roll acceleration, are in lateral equilibrium. Points in the maneuver usually investigated include a) the initiation of the aileron displacement, b) steady roll with the aileron deflected, and c) the return of the aileron to neutral.

4) Lateral-Directional Maneuver Program. This program calculates antisymmetric panel loads for maneuvers such as aileron roll, rolling pullout, rudder kicks, and engine failure. The loads are calculated in the vertical, longitudinal, and lateral directions in the body axis system, and static equilibrium is maintained in all three axes. The input is similar to the other programs except that many more "measured to theoretical" ratios are required. Also, to provide for inconsistency between the stability derivative values used in the time history analyses and the values that would be given by integrating the AIC matrix, the program was provided with options to adjust the airload distributions for consistency with the stability derivatives. This adjustment was most likely to be needed for derivatives such as $dC_n/d(pb/2V)$ (yawing moment due to roll rate) which depended upon angle of attack and therefore could not be matched with a single AIC matrix.

5) FAR Ground Maneuvers. In this program, the ground loads are reacted by rigid body translational and rotational accelerations. The program is set up to run all the FAR conditions in one run for each specified weight and center of gravity combination.

Each of the above programs runs approximately 2 min on the computer. Each computer run provides a number of conditions differing in load factor and engine power setting, but having common weights, speeds, and altitudes. It was customary to investigate both maximum and minimum specified power settings for each condition. The average 2 min computer run contained about 12 conditions.

Loads for the steady maneuvers and FAR 25 ground handling conditions were calculated soon after the basic data matrices were formulated, since this type of condition did not require prior transient time history analysis. Conditions of this type were in fact significant design conditions on major portions of the L-1011 wing, centersection, and fuselage.

Time History Analyses

For the transient maneuver conditions, it was necessary that the panel loads step be preceded by a first step involving solution of the airplane equations of motion.

These analyses were carried out using a variety of digital computer programs. These ranged from simple remote-access computer programs using a limited number of degrees of freedom, to sophisticated programs including a lateral-directional maneuver program which utilized all six rigid-airplane degrees of freedom as variables, provided for stabilizer, aileron, and rudder motions due to both pilot and stability augmentation system action, and accounted for changes of air density with altitude during the maneuver. More recently, computer-graphics scope programs, using nonlinear aerodynamics, have proved useful in rapid parametric surveys to isolate critical transient maneuvers and in correlating with flight-measured accelerations and loads in maneuvers.

Input data to the time history programs included stability derivatives adjusted to account for airplane flexibility. In making these adjustments, computer programs similar to the panel loads programs discussed above were used. The approach was to determine the distribution of airload associated with unit change of angle of attack, rotational velocity, or control surface position, alternately with and without the effects of flexibility included. The resulting airloads were then summed to give the total lift and moment. The "flexible-to-rigid" ratios thus obtained were then used to adjust the rigid-airplane stability derivative values given by wind tunnel test or other source. This approach is similar to that described in Ref. 7. Of major importance in these adjustments was the inclusion of inertia as well as aerodynamic forces in determining the structural deformations. The airloads due to acceleration have long been recognized as having a significant effect on the stability characteristics, particularly of long slender-body configurations.[8] For the L-1011, for a typical vertical gust condition (maximum zero fuel weight, structural reserve fuel, V_c speed), the ratio of flexible-airplane to rigid-airplane lift curve slopes is 0.80 when inertia effects are ignored, but increases to 0.89 when inertia effects are accounted for. The effect of inertia would be still greater for a high-fuel-weight condition. With inertia forces included, each derivative was a function of weight and weight distribution as well as dynamic pressure and Mach number. As an alternate procedure, it was possible to include only aerodynamic forces in the adjustments to the stability derivatives and then account for the effect of the inertia forces on the deformations by introducing additional terms into the differential equations. These terms would have coefficients such as dC_L/dn_z, $dC_L/d\dot{\theta}$, dC_M/dn_Z, etc. Both approaches were used in the L-1011 analysis. Inasmuch as the two approaches were theoretically equivalent, identical results were obtained from both. A further consideration in determining the stability derivative flexibility adjustments was the reference plane relative to which the deformations were considered to occur. This reference is important because its angle to the windstream defines the angle of attack. For much of the L-1011 work, the reference was chosen as the plane passing through the two points in the structure relative to which the SIC's were computed. Inasmuch as these points were centrally located in the wing-fuselage intersection region, they provided a fairly realistic reference. A theoretically sounder reference, however, is that defined by the instantaneous position of the principal axes of the deformed airplane. This form of reference was used in determining the longitudinal stability derivatives in all the later L-1011 work.

Transient maneuvers were primarily critical for parts of the horizontal and vertical stabilizers as well as the rudder and elevator. They also influenced center section, outer wing, and fuselage design. The L-1011 design criteria exceeded FAR 25 requirements for rudder maneuvers in that the structure was made adequate for rudder maneuvers based on available system output (which was lim-

Table 4 Sequence of conditions scan

Structural module	Approximate no. of panel loads conditions run (limit loads)	Potentially critical conditions (external loads scan)	Potentially critical conditions (stress scan)	Critical conditions (complete stress analysis)
Wing	4000	260	95	30
Fuselage forebody	2000	110	90	50
Fuselage aftbody	2000	180	100	50
Centersection	4000	300	140	50
Empennage	2000	110	75	45

ited as described earlier) for the entire design speed range of the airplane up to, and including, design dive speed (V_D). FAR 25 requirements were also exceeded for pitch maneuvers; structural integrity was provided for rapid excursions of horizontal stabilizer displacement in all configurations (including the flaps extended configuration) over the entire applicable design speed ranges.

Scanning and Stacking

The total number of possibly critical conditions which must be considered for loads generation is staggering. For just the routine aileron roll conditions, for example, consideration must be given to left and right wing (up vs down aileron), to several points in time including 1) the initiation of roll, 2) the steady portion of the roll, and 3) the check of the roll, and finally to all combinations of speed, altitude, gross weight, center of gravity position, and fuel weight and distribution. For conditions involving the fuselage, various payload distributions must also be considered. Manifestly, to minimize both the manpower and computer time involved in both the loads and stress analysis, a continuing effort is needed to weed out noncritical conditions.

The first stage, of course, is to monitor aerodynamic, aeroelastic, inertia, and airplane response trends over the flight envelope to eliminate obviously noncritical conditions before any panel loads are run. Even after this first stage, approximately 4000 limit load conditions remained, which were actually run on the computer to obtain panel loads.

At this point, it was vitally necessary to reduce this number, in preparation for the next step in the structural analysis, which consisted of generating internal loads (stresses) in the complex three-dimensional finite-element stress "model," for each panel loads condition. In order to reduce the number of conditions carried to this step, a systematic scanning process was conducted. This scan was accomplished in various ways. The primary method for the wing, fuselage, and empennage consisted of running the external shears, bending moments and torsions at key stations through a computer program which identified those conditions that three-dimensionally enveloped all of the conditions. These were computer plotted on shear-torsion, bending-torsion, and/or shear-bending coordinates. For the wing-fuselage intersection region, loads in key structural elements were determined by multiplying the external loads matrix by a matrix such as to yield desired internal loads; these were then scanned for maximum values. In all of the scanning, unlike groups of conditions, such as flight and ground loads conditions and conditions with and without cabin pressurization, were scanned separately.

Preliminary to the scanning operation, it was necessary to collect the panel loads for the several thousand conditions that had been run and "stack" these into a limited number of matrices on magnetic tape, containing the final panel loads only. In these matrices, the rows represent the 333 panel loads locations, while the columns represent the hundreds of design conditions. This operation alone, initially overlooked as trivial, was found to be substantial in terms of both elapsed time and effort. Then, after the external loads scan, the surviving conditions were restacked, this time into separate matrices for each structural module (wing, forebody, aftbody, centersection, and empennage). Thus a further saving in stress bookkeeping and computer time was effected. These matrices, on magnetic tape, were then transmitted to the stress organization, and internal loads (flange loads and shear flows) were determined. The internal loads at some 20,000 locations were then scanned, with the conditions giving the six highest positive and six highest negative values of each retained for detailed stress analysis. The numbers of conditions remaining after each of these stages, by module, are shown in Table 4, together with the number finally found to be critical after detailed stress analysis.

Fail-Safe Conditions

The structural fail-safe conditions defined for the L-1011 consisted of 1) structural element failure conditions, 2) system failure conditions, and 3) gear and pylon breakaway conditions. Structural element failure conditions were defined in accordance with FAR 25, at approximately 80% of the limit load level, for steady pitch, static vertical and lateral gust, and yaw maneuver conditions. Actual fail-safe design and test, however, was to full limit load (without the FAR dynamic factor of 1.15) for all flight and landing conditions. System failure conditions include such conditions as the loss of one or more actuators, the physical loss of an engine, asymmetric flaps and elevators, and spoiler malfunctions; they do not presume any structural element failures in addition. Gear and pylon breakaway conditions were defined in order to assure that if either of these components should break away under a crash landing or other emergency situation no fuel would be released.

Repeated Loads Spectra

Because of the major importance, in the design of the L-1011, of achieving a long crack-free service life, development of realistic repeated loads spectra for use in fatigue analysis and test was of comparable importance to establishing adequate limit-design loads.

Flight profiles representative of typical operational usage of the airplane were first established. These were the same as used in the gust limit loads mission analysis[1]; only a single mix was used, reflecting expected average operation of the fleet.

The loads spectra developed for the L-1011 were presented on the basis of cycles/flight. This basis was chosen in preference to cycles/hour because it appeared that fatigue life would be less dependent on flight duration if expressed in flights rather than hours.

Environmental spectra were obtained from a variety of sources. Spectra of flight maneuver load factor were based upon unpublished data from turbojet transport operations, prepared by NASA-Langley (on a per-flight basis) in 1966. The gust environment was defined in power spectral form; the same definition was used as in the gust limit load mission analysis.[1] The landing sinking speed spectrum was based on camera measurements of turbojet landings,[9] adjusted for the effect of gusty air using data from Ref. 10. The runway roughness environment was

Table 5 Airplane loads measurement tests

Flight maneuvers		Other loads tests	
Roller coasters	62	Gust	82
Wind-up turns	38	Taxi	12
Abrupt pitches	24	Landing	70
Rolling pullouts	25	Ground handling	14
Steady sideslips	17		
Abrupt rudder kicks	10		178
	176	Grand total	354

taken from Table 20 of Ref. 11; this specifies fractions of taxi time on each of three runways such that accelerations given by VGH data for existing transports were matched by analysis. For other sources of loading—in particular, transient flight maneuvers, and ground maneuvers such as turning, pivoting, braking, and engine runup—statistical data appear to be totally nonexistent. For these loadings, spectra were estimated based upon whatever information, experience, and judgment could be brought to bear. Ground turning spectra, for example, were based on examination of actual taxiing routes for three major airports.

Panel loads for the various 1g and reference varying load conditions, for all the various sources of loading, were obtained generally by the same procedures used to obtain limit loads. The 1g loads, of course, offered no problem; nor did the reference varying loads for the flight maneuver conditions, which involved increments due to a 1g load increment. Reference varying loads for the statistically defined conditions—gust and taxi—were defined by the matching condition technique described in Ref. 1, at either a given frequency of exceedance or at the limit load level. The loading spectra were then expressed as frequency of exceedance of the ratio of varying load to reference varying load. In this form, the spectra applied directly to stresses as well as to loads.

Loads Validation Tests

A variety of tests conducted at various stages of the L-1011 development provided verification of key parameters affecting the loads analysis. Shake tests, as well as deflections measured in the static strength tests, provided a check on stiffness data. An early indication of inflight elastic mode dampings and frequencies was obtained from flight flutter tests. Control system characteristics were verified in the VSS (vehicle system simulator); this simulator contained actual control system hardware laid out full scale, together with analog computer simulation of the aerodynamic reacting forces.

The landing gear drop tests, conducted at Lockheed's Rye Canyon test facility, provided the primary means of validating the landing gear loads occurring during landing impact. A series of drops was made first to establish the final orifice size (main gear) or metering pin profile (nose gear). With the final metering systems installed, 57 main gear and 36 nose gear drops were made to confirm the shock absorption characteristics in both level and tail down attitudes over a wide range of drop weights, sinking speeds, and wheel speeds and with over- and under-inflation of tires and strut.

The major source of validating data for the L-1011 design loads was an extensive program of airplane flight and ground loads measurements. A total of 354 test points was obtained, where each test point consisted of a complete maneuver, landing, turbulence sample, or taxi run. The distribution of test points is shown in Table 5. The tests covered all configurations and a wide range of weights, speeds, and altitudes, including speeds up to 430 knots.

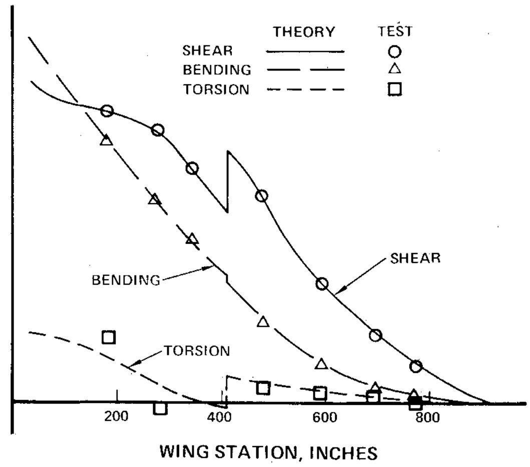

Fig. 5 Wing net loads comparison, basic configuration.

For the purpose of these tests, airplane Serial 1001 was provided with extensive strain gage instrumentation. Shear, bending, and torsion were measured at seven stations on the left wing and one on the right. The horizontal stabilizer had coverage at three stations, the vertical tail at two, and the fuselage at two. The landing gears were instrumented to measure vertical, side, and drag forces, strut torsions, strut closures, and bogie beam loads. Engine mount link loads were measured. All the primary translational and rotational velocities and accelerations, control surface positions, and control surface actuator forces were also measured.

The measurements verified the adequacy of the L-1011 limit design levels and confirmed the trends predicted by the wind tunnel force and pressure data.

For example, for steady maneuvers the wing showed good to excellent correlation with the analytical methods, especially the wing bending moments, which historically have been considered the load quantities most accurately measured by the strain gage technique. Figure 5 shows a typical comparison of measured with theoretical wing loads for the basic (clean) configuration. The agreement was nearly as good for the flaps-extended configurations. Only in the high-drag configuration (spoilers deployed as speed brakes) was the correlation not good, with the measured loads substantially lower than the analytical. With spoilers deployed, lifting-surface theory cannot be expect-

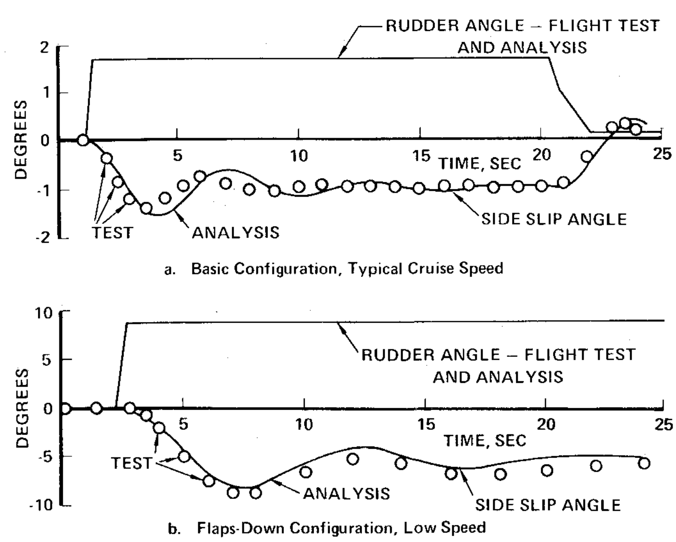

Fig. 6 Comparison of analytical and measured yaw maneuver time histories.

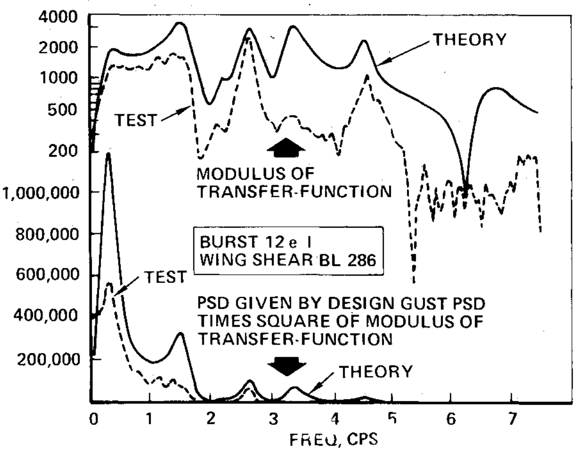

Fig. 7 Comparison of analytical and measured loads in turbulence.

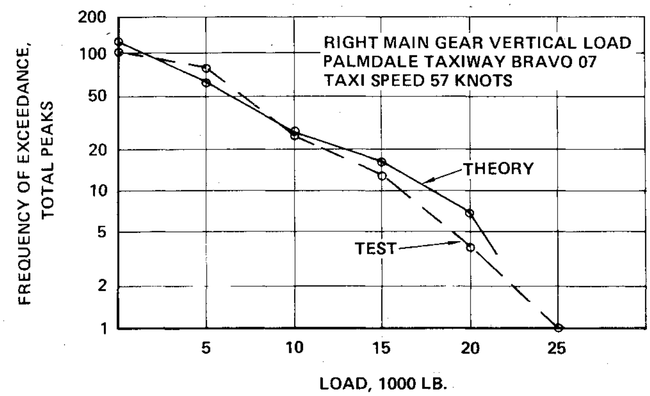

Fig. 8 Comparison of analytical and measured loads in taxiing.

ed to apply realistically, and adequate wind tunnel pressure measurements were impractical to obtain. Design loads were based on lifting surface theory, but with spoiler angles artificially increased to provide a conservative match to the wind tunnel force data.

The transient response of the airplane correlated well with the predicted. An illustration of this correlation is contained in Fig. 6, which shows the analytical and measured airplane sideslip response to ramp-type rapid rudder maneuvers for the basic configuration at high speed and the flaps extended configuration at low speed.

The primary gust loads tests were conducted with a probe mounted 23 ft ahead of the airplane nose to measure the three components of gust velocity. Sixteen samples of continuous turbulence were obtained, varying from 1 to 5 min in duration. Samples were obtained at both low altitude and normal cruise altitude, at two speeds at each altitude, over a range of fuel weights, and with yaw damper on and off. Transfer functions were obtained for 52 airplane load and other response quantities for comparison with values obtained by analysis for the same flight conditions. A sample of some of the data obtained is shown in Fig. 7.

The taxi load tests were made on a taxiway for which profiles corresponding to left gear, right gear, and nose gear tracks had been measured by conventional surveying methods. Exceedance curves of gear, wing, and fuselage loads were obtained from the test time histories and compared with curves obtained from computer time history runs using the same profiles. A sample comparison is shown in Fig. 8.

Summary

This paper has attempted to provide a brief description of certain important aspects of the structural design criteria and loads analysis methods applied to the Lockheed L-1011 TriStar. It has touched on the basic panel loads approach, the data requirements, the phases of the analysis, and the details of the static aeroelastic loads analyses, as well as the fail-safe design and repeated loads spectra. The test programs which supported, influenced, and validated the loads analysis have also been discussed. The discussion has been limited to primary structure; the many secondary analyses needed to provide design loads for such items as flaps, slats, doors, etc., as well as the extensive analyses for ditching and crashlanding conditions, were considered beyond the scope of this paper. Considerable time and effort have been expended to meet or exceed all FAA and ARB requirements and to provide structural criteria and loads that will result in a safe and economical airplane structural design, compatible with the environment in which the airplane will operate.

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