NASA Contractor Report 3585

Nacelle Aerodynamic and Inertial Loads (NAIL) Project

Summary Report

Staff of Boeing Commercial Airplane Company

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Staff of Boeing Commercial Airplane Company
Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contract NAS1-15325

National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

1982

FOREWORD

This report presents a brief summary of the Nacelle Aerodynamic and Inertial Loads (NAIL) project. A complete report of the NAIL project appears in the Final Technical Report (ref. 1). The work was conducted under NASA contract NAS1-15325 from October 1979 through August 1981. The contract was managed by the NASA Energy Efficient Transport Office (EETPO), which is headed by R. V. Hood and which is a part of the Aircraft Energy Efficiency (ACEE) program organization at Langley Research Center. D. B. Middleton and K. W. Heising were the technical monitors for the contract. The work was performed in the Engineering and the Flight Operations organizations of Boeing Commercial Airplane Company. Key contractor personnel responsible for the material in this report were:

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The test effort was conducted in cooperation with Pratt & Whitney Aircraft Group, which was supported by NASA-Lewis Research Center under contract NAS3-20632.

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1.0 SUMMARY

The Nacelle Aerodynamic and Inertial Loads (NAIL) project consisted of two distinct tasks. They were the flight loads study and the installed propulsion system aerodynamics (IPSA) study.

1.1 FLIGHT LOADS

The NAIL flight loads study comprised a series of flight tests to measure the aerodynamic and inertial loads imposed on the Pratt & Whitney JT9D-7 turbofan engines of a Boeing 747 airplane under conditions of flight acceptance testing and of typical revenue service. Aerodynamic loads were determined by integrating pressures measured at 252 locations on the right-hand inboard engine inlet and fan cowl. The relative load level on the right-hand outboard engine was established by 45 pressure measurements, which were compared with the corresponding inboard engine pressures. Inertial loads were determined by sets of linear accelerometers mounted on the engines and inlets and on the wing at the nacelle strut attach points and by rate gyros mounted on the engine fan cases.

The purpose of the measurements was to clarify the influence of flight loads on engine performance deterioration due to enlarged rotor tip clearances caused by the rotor rubbing on the engine case under load. Rotor/case clearances were measured in flight by laser probes mounted on the fan and high-pressure turbine case of the inboard engine and on the fan case of the outboard engine. Airplane flight condition data and engine performance data were measured and recorded for all flight conditions. (This document deals only with the measured flight loads. Correlation of these loads with clearance changes and analysis of engine performance effects are reported separately in refs. 2 and 3.) Aerodynamics and inertial loads were estimated prior to flight test (ref. 4).

Inlet aerodynamic pitching moments were measured for a group of flight conditions typical of a transport mission and for a group of conditions characteristic of a 747 acceptance test flight. It was found that:

- The severest operating airloads occur during takeoffs.
- Airloads were generally larger than were estimated, and inertial loads were smaller.
- Calculations based on measured inlet airload sensitivity to change in angle of attack indicate that transient inlet airloads due to gusts are considerably smaller than takeoff airloads.
- Airloads can be significantly reduced by revisions to flight procedures.

The pressure data were also tabulated in computer data files suitable for finite-element analyses of engine/nacelle structures and provided to Pratt & Whitney for correlation of measured and calculated clearance changes. (This effort will be reported separately by Pratt & Whitney.)

To permit application of the NAIL loads data to aircraft/engine combinations other than the 747/JT9D, the vertical force and pitching moments at high angle of attack and airflow were expressed as aerodynamic coefficients and correlated with estimated inlet angle of attack and nondimensional engine airflow. The resulting expressions can be used to estimate inlet airloads for any roughly similar inlet geometry, provided the inlet angle of attack is known.

1.2 INSTALLED PROPULSION SYSTEM AERODYNAMICS (IPSA)

The IPSA portion of the NAIL project created a data base of pressures measured on the inlets, cowls, struts, and adjacent wing surfaces of the two right-hand engines of a Boeing 747. These data, along with the aerodynamic geometry definition, will be used to develop and to verify analytical flow models and computer codes to be employed in the design of propulsion system aerodynamic configurations having reduced interference drag.

In the course of three test flights, pressure data were obtained for Mach numbers 0.77, 0.80, 0.86, and 0.91 at lift coefficients corresponding to cruising flight.

2.0 INTRODUCTION

2.1 BACKGROUND

2.1.1 Flight Loads

The thrust-specific fuel consumption (TSFC) of the turbofan engines on commercial transport aircraft deteriorates in service. When fuel was cheap and plentiful, an increase in TSFC was merely a nuisance, but the shortages and price increases following the 1973 oil embargo made TSFC increases a serious issue. Accordingly, the NASA Engine Component Improvement (ECI) program (part of the NASA Aircraft Energy Efficiency program) was made responsible for determining the cause of and potential solutions to installed engine TSFC deterioration. As part of the ECI program, Boeing Commercial Airplane Company (BCAC) assisted Pratt & Whitney Aircraft Group (P&WA) under a NASA-Lewis contract in an investigation of this problem (ref. 3).

It was found that early deterioration was due primarily to rotor blade tips rubbing against the engine casing as the engine deformed under its operating loads. This rubbing caused increased clearances and gas flow leakage, resulting in a cruise TSFC deterioration of about 0.8% after the predelivery acceptance testing and an additional 0.3% in 2000 flights in revenue service.

Development of a means to reduce deterioration required identification of the particular operating loads responsible for the rubbing. On the basis of the sketchy data then available, it was estimated that 87% of the deterioration in the first 1000 flights was due to aerodynamic loads acting on the inlet. To confirm this, a flight test program was defined in which loads and rotor clearance changes would be measured at the same time (ref. 5). NASA-Langley and NASA-Lewis Research Centers authorized and jointly funded this program under separate contracts for BCAC and P&WA. The BCAC effort, the Nacelle Aerodynamic and Inertial Loads (NAIL) project, was funded by NASA-Langley and NASA-Lewis under task 4.3 of contract NAS1-15325. The P&WA effort was funded by NASA-Lewis.

2.1.2 Installed Propulsion System Aerodynamics (IPSA)

The installation of propulsion systems on aircraft wings causes a drag increment called interference drag, which results from flow processes near the nacelle, wing, and pylon. Numerical solution methods are being developed for the governing equations of transonic flow about such groups of bodies. These methods are expected to permit rational design of propulsion installation having greatly reduced interference drag. A comprehensive data base of the flow properties around a propulsion system installed near a wing was needed to validate the analytical results and to highlight modeling inadequacies.

The NAIL flight loads program provided instrumentation capable of measuring a substantial portion of the pressures needed for the IPSA study. It was logical and economical to expand the scope of NAIL to include IPSA; and contract NAS1-15325, between NASA-Langley Research Center and BCAC, was revised accordingly.

2.2 OBJECTIVES

The objectives of the flight test program were to:

- Measure flight loads (aerodynamic and inertial) typical of the production acceptance flight (a substantial contributor to short-term deterioration) and revenue service

- Explore the effects on nacelle loads of gross weight, pitch and yaw rate, touchdown sink rate, and various maneuvers

- Measure simultaneously engine clearance closures and engine performance changes

- Provide a data base for designing improved propulsion systems (performance retention)

- Provide a data base of pressures measured on wing, pylon, and nacelle surfaces of both inboard and outboard propulsion installations of commercial transport-sized aircraft and gather information on airflow patterns surrounding the powerplant installations using static pressure surveys

2.3 APPROACH

A 15-hour flight test program covering the entire acceptance flight profile, variations in takeoff and landing conditions, and high-g turns was defined to measure simultaneously the flight loads (cause) and engine clearance changes (effect) associated with engine performance deterioration. The testing was conducted on the Boeing-owned 747 RA001 test bed airplane (fig. 1).

Figure 1. RA001 Test Airplane

Inertial loads were measured by accelerometers and rate gyros on the right-hand wing and engines. The engine clearance changes were measured by laser proximity probes on the fan of both engines and on the high-pressure turbine of the inboard engine. Aerodynamic loads were measured by integrating pressures measured at 252 taps on the right-hand inboard nacelle. Loads for the right-hand outboard nacelle were monitored by comparing pressures measured at 45 taps to those measured at corresponding locations on the inboard nacelle.

IPSA pressures were measured on both of the right-hand pylons and core cowls and on the adjacent wing surfaces. In addition, pressures measured at a large number of the taps installed for the flight loads effort (located on the inlet and fan cowl) were applicable to IPSA. A total of 557 pressure measurements were obtained for each IPSA flight condition.

3.0 SYMBOLS AND ABBREVIATIONS

ACEE	Aircraft Energy Efficiency Program
BCAC	Boeing Commercial Airplane Company
ECI	NASA Engine Component Improvement program
F_x	force in x-direction (see fig. 7)
F_y	force in y-direction (see fig. 7)
g	load factor
GW	gross weight
IPSA	installed propulsion system aerodynamics
IRIG	interrange instrumentation group master clock
kcas	knots calibrated airspeed
M_C	design cruise Mach number
M_D	design dive Mach number
M_x	moment about the x-axis (see fig. 7)
M_y	moment about the y-axis (see fig. 7)
NAIL	Nacelle Aerodynamic and Inertial Load Program
P&WA	Pratt & Whitney Aircraft Group, Commercial Products Division
q	dynamic pressure
RWA	referred airflow
TSFC	thrust-specific fuel consumption
V_C	design cruise speed
V_D	design dive speed
α_{VANE}	airflow sensor vane angle

4.0 RESULTS AND DISCUSSION

4.1 TEST DESCRIPTION

The Nacelle Aerodynamic and Inertial Load (NAIL) program consisted of two distinct efforts: the flight loads test and the installed propulsion system aerodynamics (IPSA) test. Both were conducted concurrently with JT9D-7R4 nacelle and engine development tests for the 767 program on the Boeing-owned 747 RA001 airplane (fig. 1). Separate data collection systems were used for the two tests, although substantial portions of the flight loads data applied also to IPSA. Airplane and engine performance data applicable to both tests were gathered from instrumentation and data acquisition systems already available in RA001.

4.1.1 Instrumentation

Instrumentation placed on or near engines 3 and 4 was designed to further the understanding of the flight loads (cause) and engine clearance changes (effect) associated with engine deterioration and to provide information on the flight environment of the engine and wing interface.

Engine 3, the right-hand inboard engine, was chosen for greater emphasis because slightly more severe loads were expected at the inboard location and position 2 was not available. Engine 3 was fitted with a specially built turbine case equipped with laser proximity probes, another set of laser proximity probes in the fan case, and an inlet containing comprehensive pressure measuring instrumentation (fig. 2).

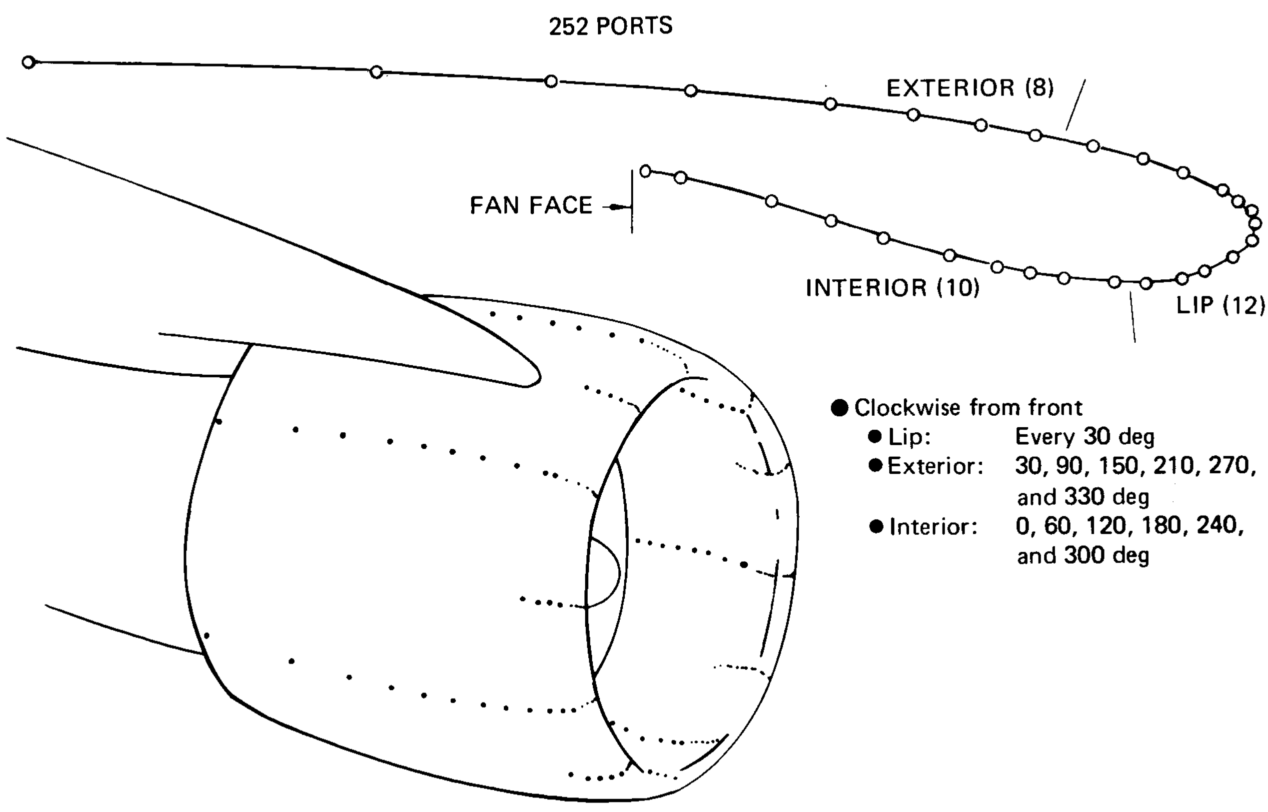

Figure 2. Inboard Engine Pressure Taps

Engine 4, the right-hand outboard engine, was fitted with a rebuilt fan case containing a set of laser proximity probes and an inlet with sufficient pressure instrumentation to determine airloads relative to engine 3.

Instrumentation for inertial loads consisted of accelerometers and rate gyros located on the engine and pylon (fig. 3) and near the aircraft center of gravity.

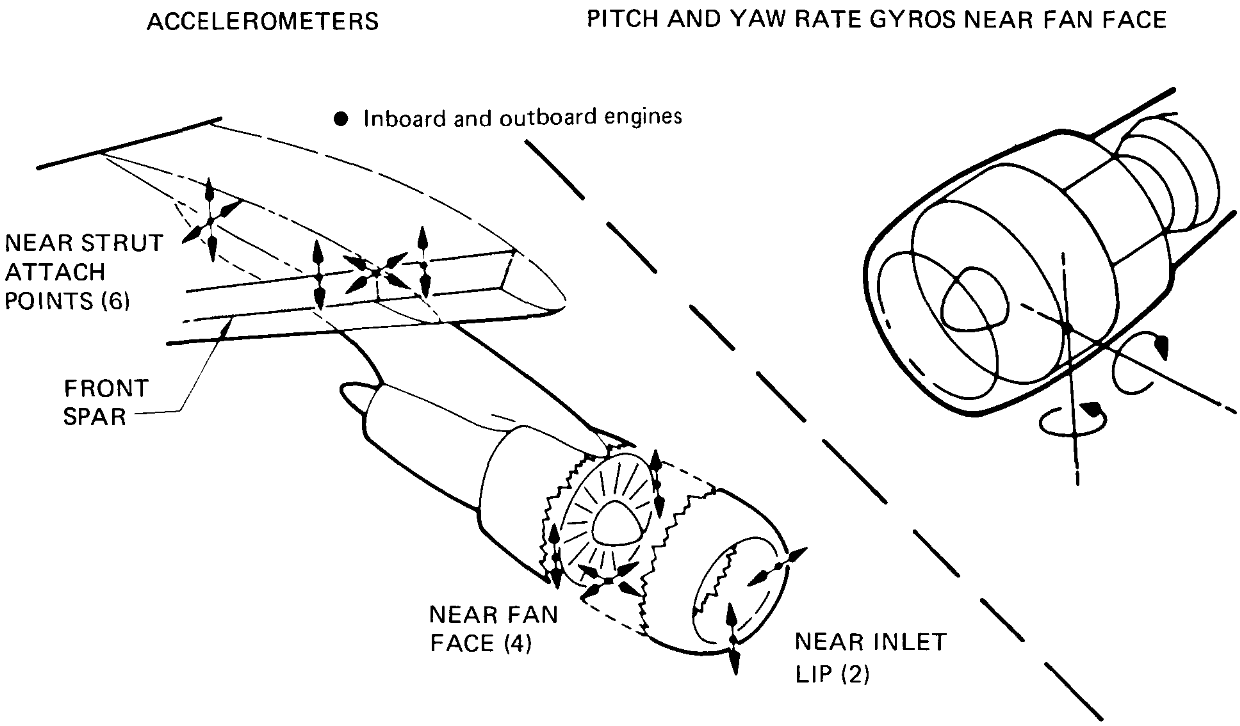

Figure 3. Inertial Data Sensors

Engine clearance change measurements were made by Pratt & Whitney Aircraft Group (P&WA) simultaneously with flight load application. Measurements were made on the fan and first-stage high-pressure turbine on the inboard engine and the fan stage of the outboard engine by a laser proximity system for each stage. Each clearance monitoring system consisted of the laser assembly, the input fiber-optic assembly, video camera assembly, laser probe assembly (four probes per stage), video monitor, and video tape recorder (fig. 4).

In addition to the inlet and fan cowl pressure instrumentation already provided under the flight loads portion of the program, IPSA required pressure measurements on the inboard and outboard pylons, core cowls, and wings. The wing pressures were measured using external tubing in three streamwise strips on the upper surface at each nacelle (fig. 5) plus two on the lower surface on either side of the pylons. Internally mounted pressure taps were located on the pylons and core cowls.

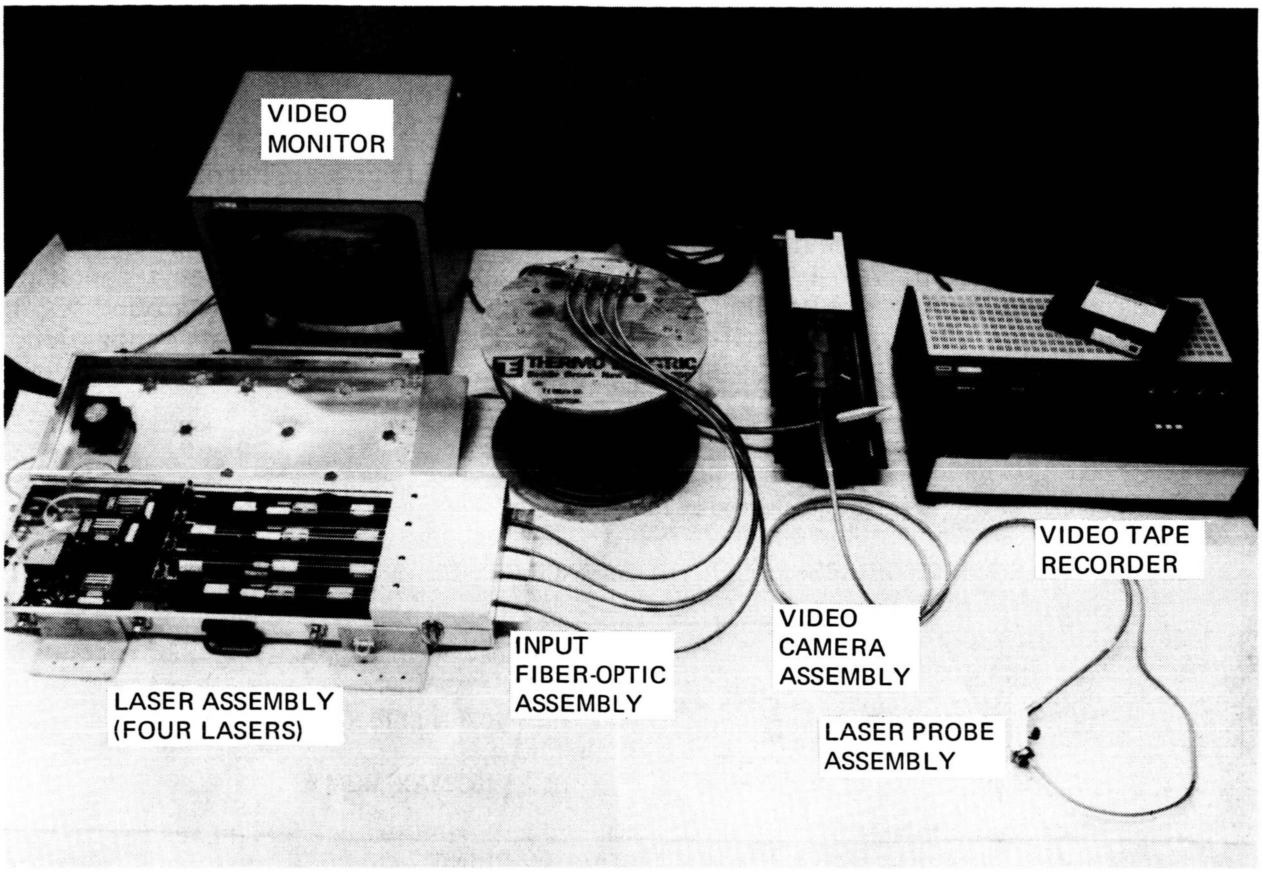

Figure 4. Blade-Tip Clearance Monitoring System

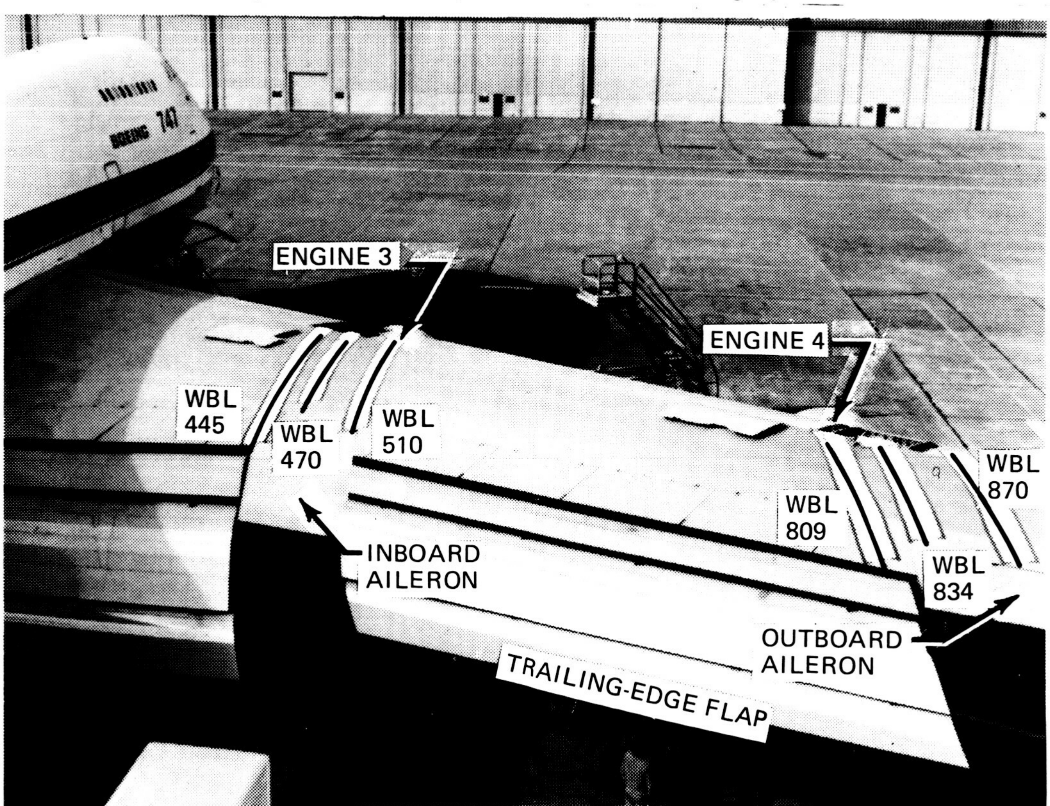

Figure 5. IPSA Wing Pressure Measurement Locations

4.1.2 Test Conditions and Procedures

4.1.2.1 Flight Loads

It was suspected that the first 1% loss in performance due to engine clearance changes occurred during the production acceptance flight test profile (fig. 6). Therefore, a typical acceptance test profile was chosen as the basis of the first test flight (ref. 6). Subsequent flights contained high-g turns and variations in takeoff gross weight. Because of takeoff weight limitations on the 747-100 airframe, the highest gross weight takeoff condition was simulated in a symmetrical pullup maneuver at 305m (1000 ft) above ground level. Ground calibration was required after each test series. Using these calibrations, performance deterioration was determined for each series of tests. A final ground calibration was performed after completing all flight testing.

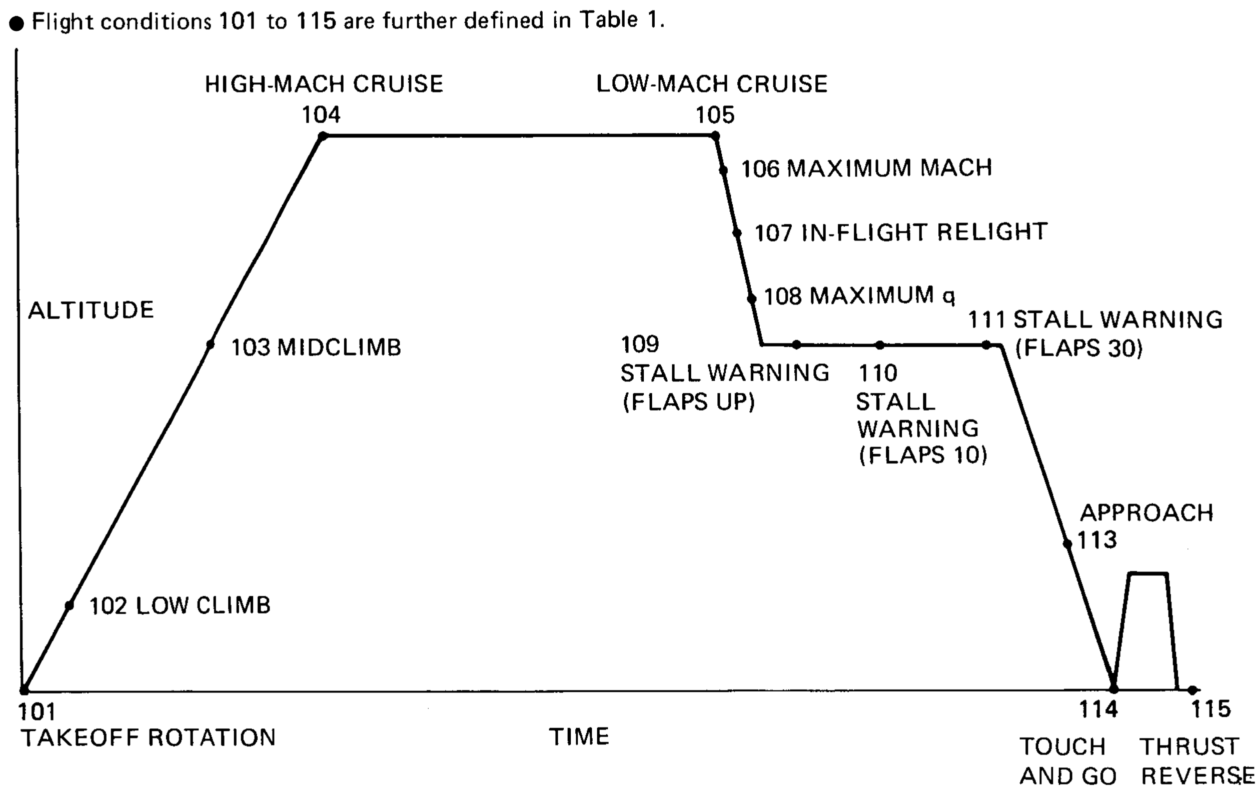

Figure 6. Acceptance Flight Profile

The test conditions flown (table 1) resulted from compromise and various flight restrictions. Originally NAIL was to be a standalone flight program. However, the flight test was conducted concurrently with the 767/JT9D-7R4 test program, which imposed certain flight restrictions on RA001. The most significant restrictions were to remain within the 767 design cruise speed and Mach number (V_C and M_C) limits of 667 km/h (360 kn) calibrated airspeed and M = 0.86 until the completion of all JT9D-7R4 test conditions and to limit nacelle loads to 80% of the design limit. Upon completion of the JT9D-7R4 program, the 767 design envelope V_D and M_D limits of 778 km/h (420 kn) calibrated airspeed and M = 0.91 were applied to the NAIL program.

Table 1. Test Conditions Flown

Test condition	Test No.	Event time	Pressure altitude, m (ft)	Mach No.
101 277.6t (612 000 lb) GWTO (flaps 20)	273-7	6:41:44	778.2 (2 553)	0.250
101 244.0t (538 000 lb) GWTO (flaps 10)	273-10	9:44:10	812.9 (2 667)	0.239
101 293.5t (647 000 lb) GWTO (flaps 10)	273-11	10:13:52	802.8 (2 634)	0.254
118 353.8t (780 000 lb) GW simulated TO (flaps 10)	273-15	8:13:18	1 111.3 (3 646)	0.296
102 Low climb	273-10	9:46:00	1 786.4 (5 861)	0.367
103 Midclimb	273-7	7:28:44	5 238.6 (17 187)	0.599
104 High-M cruise	273-7	7:49:26	10 814.6 (35 481)	0.859
105 Low-M cruise	273-7	7:56:40	10 824.1 (35 512)	0.772
106 Max M	273-15	12:09:27	11 270.9 (36 978)	0.906
107 In-flight relight	273-7	8:12:53	8 491.4 (27 859)	0.721
108 Maximum q	273-15	11:39:00	7 471.6 (24 513)	0.836
109 Stall warning (flaps up)	273-7	8:18:58	5 170.7 (16 964)	0.391
110 Stall warning (flaps 10)	273-7	8:22:26	4 949.7 (16 239)	0.347
111 Stall warning (flaps 30)	273-7	8:24:52	5 196.5 (17 049)	0.270
112 Idle descent	273-7	8:28:56	2 575.6 (8 450)	0.439
113 Approach	273-7	8:34:27	1 829.7 (6 003)	0.265
114 Touch and go	273-7	8:40:36	780.6 (2 561)	0.263
115 Thrust reverse	273-7	8:46:00	780.6 (2 561)	0.179
116 2.0g left turn (flaps up)	273-10	13:33:58	2 559.4 (8 397)	0.487
117 1.6g left turn (flaps 30)	273-10	13:41:07	2 500.0 (8 202)	0.260
120 2.0g right turn (flaps up)	273-15	11:04:03	2 511.5 (8 240)	0.476
121 1.6g right turn (flaps 30)	273-15	11:07:25	2 523.1 (8 278)	0.266
123 Airplane stall	273-10	13:26:17	2 743.2 (9 000)	0.207

As a result of the concurrent testing programs, data were taken over approximately 33 hours of flight time instead of over the initially planned 15-hour maximum. The increased flight time resulted in a substantially larger quantity of data to survey and select from and provided additional conditions for analysis.

4.1.2.2 Installed Propulsion System Aerodynamics (IPSA)

Four test conditions were flown in the IPSA portion of the project. Three were in level flight at Mach 0.77, 0.80, and 0.86. The fourth was a shallow dive at Mach 0.91. All were flown at representative cruise altitudes and lift coefficients.

4.2 TEST RESULTS

4.2.1 Aerodynamic Loads

Detailed understanding of the effects of aerodynamic loads on engine performance deterioration requires the use of finite-element analysis methods. Pressures on the inlet and cowl were recorded for all test conditions and transmitted to P&WA for use in such analyses, the results of which are reported in references 2 and 3.

Aerodynamic influences on the engine structure may be discussed, however, in terms of the resultant airloads determined by integration of pressures over the inlet surfaces because the engine inlet is mounted directly to the front flange of the engine fan case (the A-flange), and inlet loads must be carried to the strut through the engine case itself. Table 2 gives the integrated resultant airloads, along with key airplane and engine parameters, for 23 flight conditions. Figure 7 shows the coordinate system and sign conventions used. Note that the coordinate axis labels are not those commonly used for airplane body axes. In this report, the z axis coincides with the engine shaft axis and is positive aft. The x (vertical) axis is defined by the intersection of the center plane of the nacelle strut and the plane of the engine front face and is positive upward. This axis is normal to x and z and is positive inboard. (This is a right-handed system for engine positions 3 and 4. Nose up pitching moments are negative.)

The most important load component is the pitching moment. Figure 8 compares pitching moments for all 23 flight conditions. Note that the takeoff loads predominate. The only other conditions in which the takeoff load level is approached are the flaps 10 stall warning maneuver and the airplane stall. Neither of these conditions occurs in a typical revenue flight.

Closer examination of two particular flight conditions reveals the parameters that govern inlet airloads. Figure 9 shows time histories of inlet pitching moment, engine airflow, and airflow vane angle during the flaps 10 stall warning maneuver. (The airflow vane is a flow angle sensor mounted on the side of the body near the flight deck. The angle it measures, α_{VANE}, is related to, but not the same as, airplane angle of attack.)

In this maneuver, which is designed to verify the correct functioning of the stall warning stick-shaker system, the pilot gradually reduces speed in level flight until the system is actuated. The pilot then recovers from the incipient stall condition by pushing the nose down and adding power to prevent excessive altitude loss. At the beginning of the maneuver, the loads are quite low even through α_{VANE} is more than 20 deg. In the early (pushover) phase of the maneuver, the pitching moment declines slightly as α_{VANE} drops. However, when the engine spools up and airflow increases, the airloads rise in step with it, reaching almost -35 000 N-m (-300 in-kip).

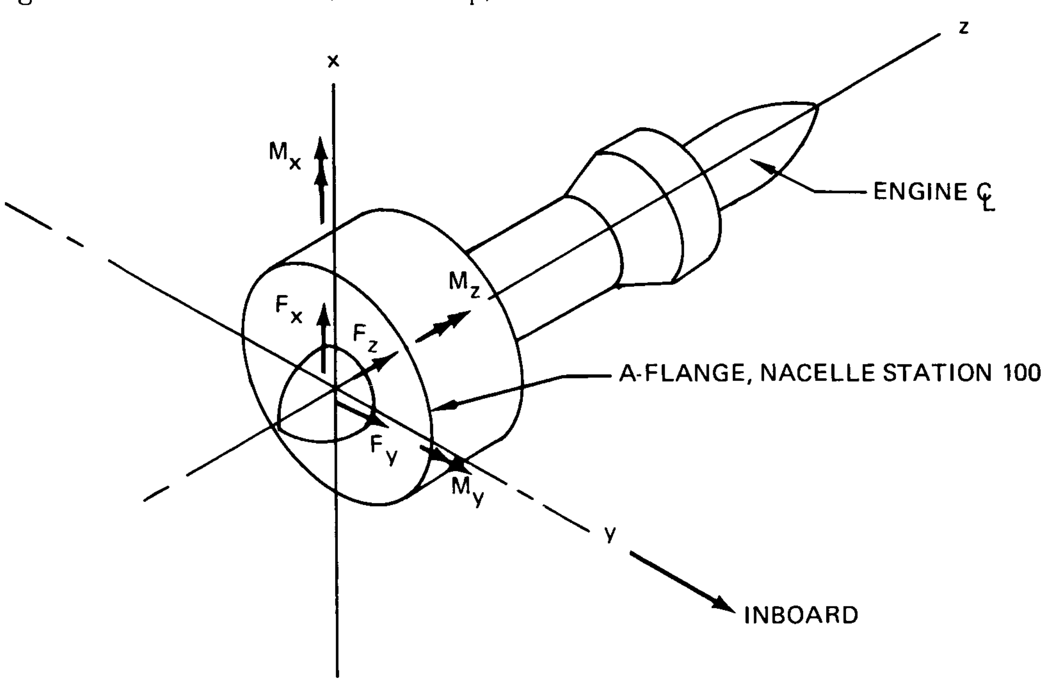

Figure 7. Sign Convention for Steady-State Loads

Table 2. Engine 3 Resultant Airloads

Condition	Calibrated airspeed km/h (kcas)	Pressure altitude, m (ft)	Mach No.	Referred airflow, kg/s (lb/s)	Load factor, g	$F_{x'}$, N (lb)	$F_{y'}$, N (lb)	$M_{x'}$, N-m (in-lb)	$M_{y'}$, N-m (in-lb)
101 Takeoff, 277.6t (612 000 lb) GW (flaps 20)	292.4 (157.8)	778.1 (2 553)	0.250	702.6 (1 549)	1.14	26 694 (6 001)	-12 250 (-2 754)	-16 692 (-147 736)	-37 148 (-328 780)
101 Takeoff, 244.0t (538 000 lb) GW (flaps 10)	279.8 (151.0)	812.9 (2 667)	0.239	692.6 (1 527)	1.26	32 012 (7 197)	-12 970 (-2 916)	-17 207 (-152 292)	-45 280 (-400 756)
101 Takeoff, 293.5t (647 000 lb) GW (flaps 10)	296.7 (160.1)	802.8 (2 634)	0.254	691.3 (1 524)	1.17	35 233 (7 921)	-13 842 (-3 112)	-18 002 (-159 325)	-48 018 (-424 987)
118 Simulated takeoff, 353.8t (780 000 lb) GW (flaps 10)	340.2 (183.6)	1 111.3 (3 646)	0.296	713.5 (1 573)	1.20	37 114 (8 344)	-12 263 (-2 757)	-15 145 (-134 045)	-48 602 (-430 154)
102 Low climb	405.5 (218.8)	1 786.4 (5 861)	0.367	698.1 (1 539)		20 772 (4 670)	-4 746 (-1 067)	-5 125 (-45 361)	-23 280 (-206 043)
103 Midclimb	538.2 (290.4)	5 238.6 (17 187)	0.599	735.7 (1 622)		18 166 (4 084)	-2 615 (-588)	-2 910 (-25 756)	-14 224 (-125 891)
104 High-M cruise	539.8 (291.3)	10 814.6 (35 481)	0.859	740.7 (1 633)		10 982 (2 469)	-4 551 (-1 023)	-4 103 (-36 317)	-6 716 (-59 441)
105 Low-M cruise	478.7 (258.3)	10 824.1 (35 512)	0.772	727.6 (1 604)		15 470 (3 478)	-5 031 (-1 131)	-4 772 (-42 237)	-11 994 (-106 150)
106 Max M	554.1 (299.0)	11 270.9 (36 978)	0.906	744.8 (1 642)		1 343 (302)	-2 064 (-464)	-1 783 (-15 779)	2 183 (19 317)
107 In-flight relight	529.5 (285.7)	8 491.4 (27 859)	0.721	619.2 (1 365)		14 576 (3 277)	-3 274 (-736)	-2 897 (-25 639)	-9 587 (84 847)
108 Maximum q	662.5 (357.5)	7 471.6 (24 513)	0.836	733.5 (1 617)		-6 272 (-1 410)	4 377 (984)	3 283 (29 060)	11 119 (98 411)
109 Stall warning (flaps up)	349.1 (188.4)	5 170.7 (16 964)	0.391	721.7 (1 591)		24 184 (5 437)	-6 156 (-1 384)	-7 206 (-63 775)	-27 480 (-243 214)
110 Stall warning (flaps 10)	313.6 (169.2)	4 949.7 (16 239)	0.347	735.3 (1 621)		27 707 (6 229)	-9 528 (-2 142)	-10 962 (-97 024)	-34 435 (-304 770)
111 Stall warning (flaps 30)	239.6 (129.3)	5 196.5 (17 049)	0.270	740.7 (1 633)		17 467 (3 927)	-5 747 (-1 292)	-8 236 (-72 893)	-24 940 (-220 730)
112 Idle descent	462.7 (249.7)	2 575.6 (8 450)	0.439	339.3 (748)		18 370 (4 130)	-5 000 (-1 124)	-3 352 (-29 669)	-10 986 (-97 234)
113 Approach	291.7 (157.4)	1 829.7 (6 003)	0.265	701.7 (1 547)		16 489 (3 707)	-6 276 (-1 411)	-8 091 (-71 607)	-22 807 (-201 854)
114 Touch and go	308.6 (166.5)	780.6 (2 561)	0.265	720.8 (1 589)		19 518 (4 388)	-10 324 (-2 321)	-14 194 (-125 622)	-27 304 (-241 654)
115 Thrust reverse	209.8 (113.2)	780.6 (2 561)	0.179	621.0 (1 369)		196 (44)	-144 (-10)	-1 954 (-17 298)	-4 628 (-40 963)
116 2.0g left turn (flaps up)	514.3 (277.5)	2 559.4 (8 397)	0.487	708.5 (1 562)	1.99	32 079 (7 212)	-15 386 (-3 459)	-15 060 (-133 292)	-29 850 (-264 186)
117 1.6g left turn (flaps 30)	265.0 (143.0)	2 500.0 (8 202)	0.260	698.1 (1 539)	1.61	23 543 (5 293)	-16 333 (-3 672)	-21 605 (-191 221)	-32 151 (-284 557)
120 2.0g right turn (flap up)	504.3 (272.1)	2 511.6 (8 240)	0.476	542.5 (1 196)	2.04	33 956 (7 634)	-7 246 (-1 629)	-5 362 (-47 455)	-27 058 (-239 481)
121 1.6g right turn (flaps 30)	280.4 (151.3)	2 523.1 (8 278)	0.266	650.9 (1 435)	1.60	24 090 (5 416)	-1 597 (-359)	-1 142 (-10 105)	-31 865 (-282 023)
123 Airplane stall	214.4 (115.7)	2 743.2 (9 000)	0.207	703.5 (1 551)		27 008 (6 072)	-7 175 (-1 613)	-10 076 (-89 181)	-41 446 (-366 818)

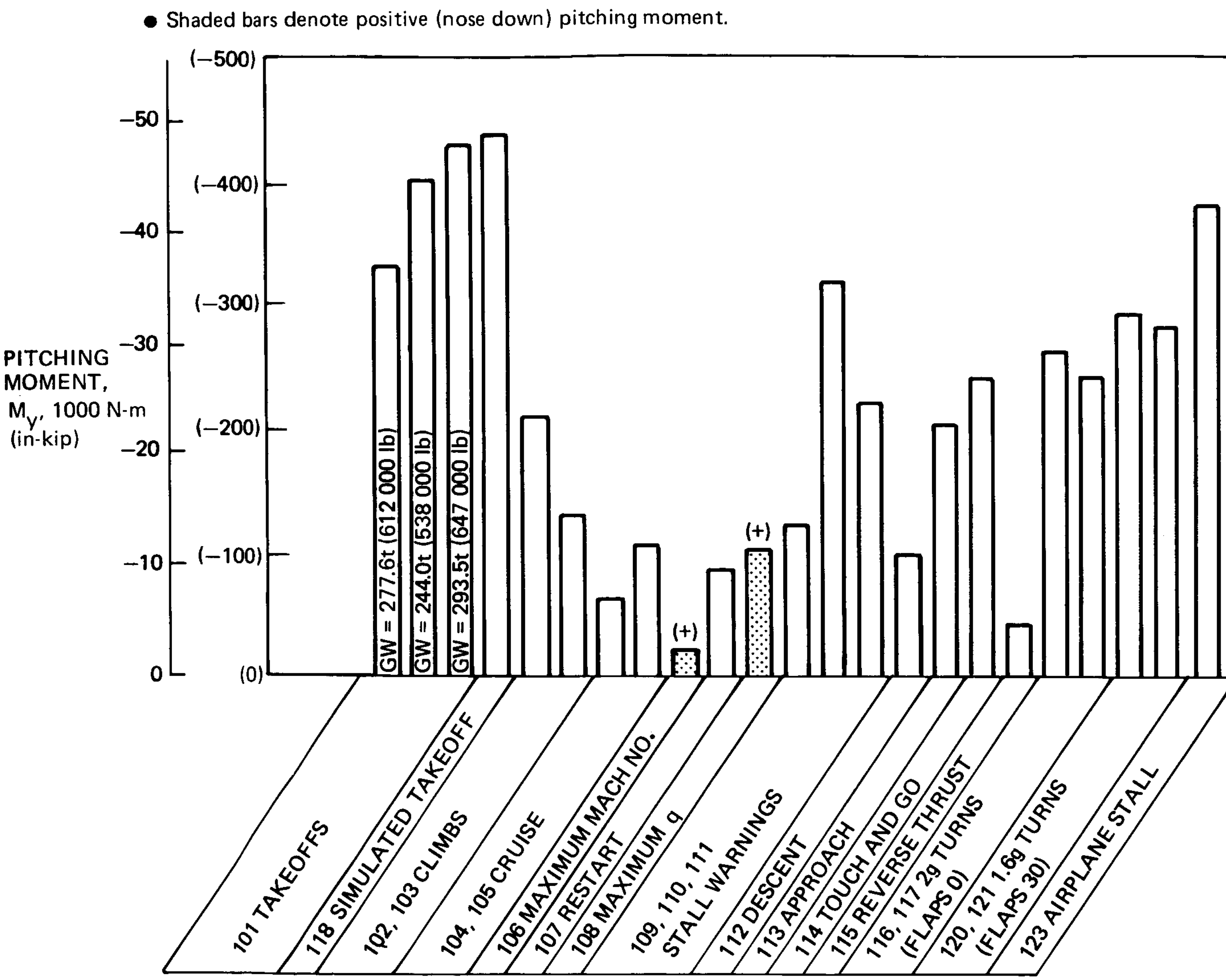

Figure 8. Airload Moment Comparison

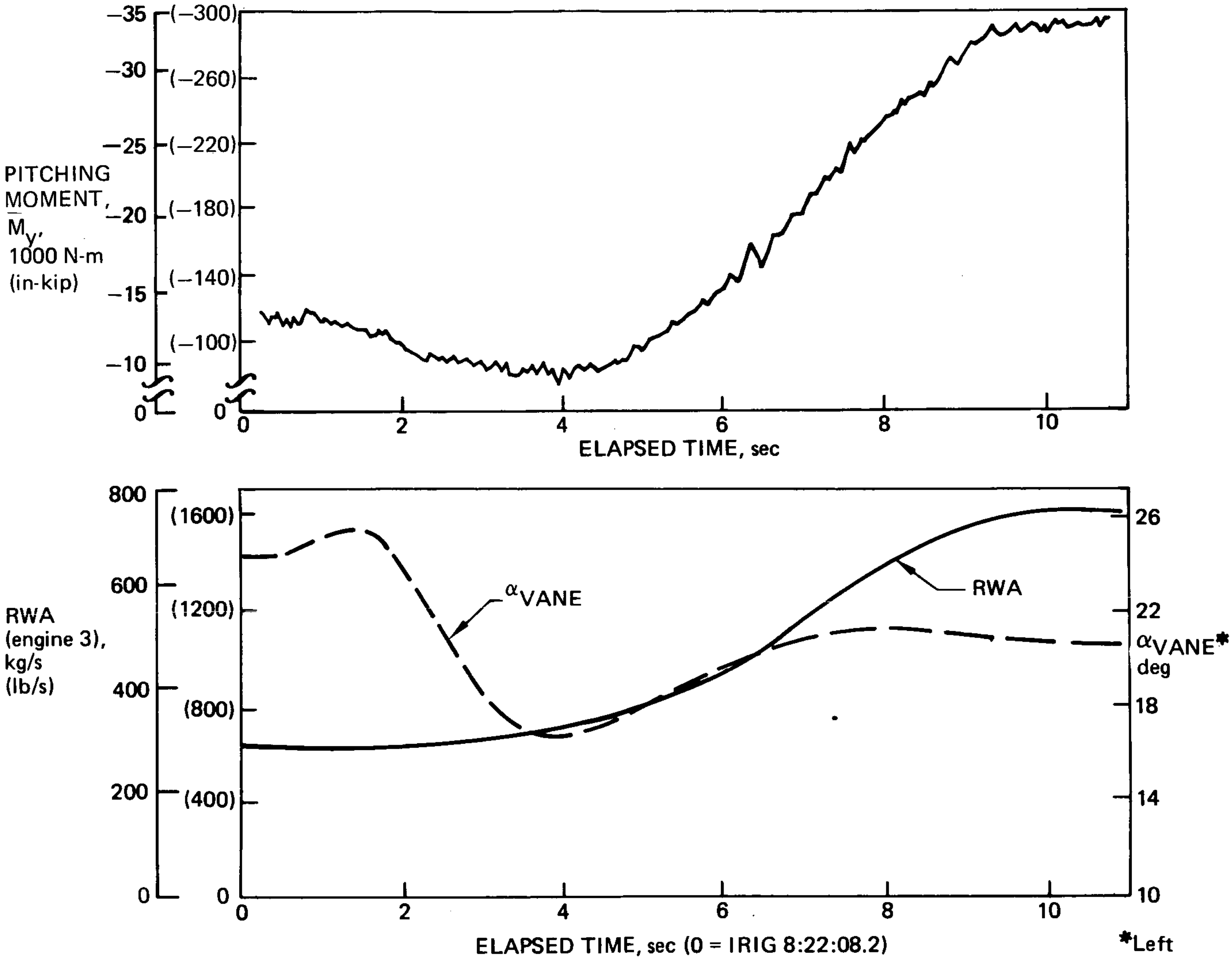

Figure 9. Relation of Inlet Airload Pitching Moment to Angle of Attack and Airflow, Stall Warning Maneuver (Flaps 10)

Figure 10 shows a time history of moments, engine airflow, and airspeed over an entire takeoff, followed by the pullup maneuver simulating the high gross weight takeoff. It is seen that although the airflow reaches a high level early in the takeoff ground roll, the inlet airload remains quite low until takeoff rotation, when it rises abruptly. It is apparent, therefore, that inlet loads respond to the combined effects of angle of attack and airflow.

The initial maximum pitching moment is reached at 59 seconds elapsed time at the moment of maximum normal acceleration (about 1.2g) in the takeoff rotation. (Note that the initial maximum yawing moment, M_x, occurs several seconds earlier.) M_y declines as the normal acceleration drops back to 1.0g and then increases again when the power setting is adjusted upward at about 72 seconds. The second airload maximum is reached at the peak normal acceleration in the pullup maneuver. In this case, M_y and M_x are synchronized. The explanation for the mismatch of peak moments in the takeoff rotation is ground effect. The yawing moment responds to local sideslip angle, just as pitching moment responds to inlet angle of attack. There is a local sideslip component due to the basic circulation pattern around the wing, and another due to the proximity of the trailing-edge flaps to the ground plane, forcing an outward flow in the early phase of takeoff rotation. After liftoff, the second component vanishes, and M_x declines.

Pressures measured on the outboard engine differed only slightly from those measured on the inboard engine for all conditions, so the airloads on the two engines may be considered equal.

No appreciable turbulence was encountered in the flight program. Nevertheless it was possible to calculate the sensitivity of inlet airloads to gusts from the measurements made in the simulated maximum-q (pushover) maneuver. For a maximum airspeed condition (694.5 km/h [375 kn] at 6096m [20 000 ft] altitude), a gust that could be expected about once in 800 hours of flying (ref. 7) would cause a pitching moment change of 22 600 N-m (200 000 in-lb). This is about half the pitching moment experienced routinely at takeoff.

To apply the loads data measured in the NAIL project to airplane and engine combinations other than the Boeing 747 and Pratt & Whitney JT9D-7 combination, the vertical force and pitching moment for 31 low-speed flight conditions were expressed as nondimensional aerodynamic coefficients and were correlated against inlet angle of attack and nondimensional engine airflow. The resulting formulas fit the data with a root-mean-square error of 5% of typical takeoff force and moment levels (ref. 1).

4.2.2 Inertial Loads

Inertial loads recorded at all flight conditions were provided to P&WA to be used in combination with airload data in analyses of clearance changes and performance deterioration. Inertial loads were generally less severe than those estimated in reference 4.

4.2.3 Installed Propulsion System Aerodynamics (IPSA)

Surface static pressures were measured on the right-hand nacelles, pylons, and neighboring wing surfaces in three separate test flights. Data were acquired at M = 0.77, 0.80, and 0.86 during the initial IPSA flight, test 273-09. Instrumentation problems revealed in this test were partially corrected for during the second flight, test 273-12, in which data were acquired at the same test conditions. The third flight, test 273-15, was flown primarily to fulfill the remaining test condition (Mach 0.91) after the speed restriction

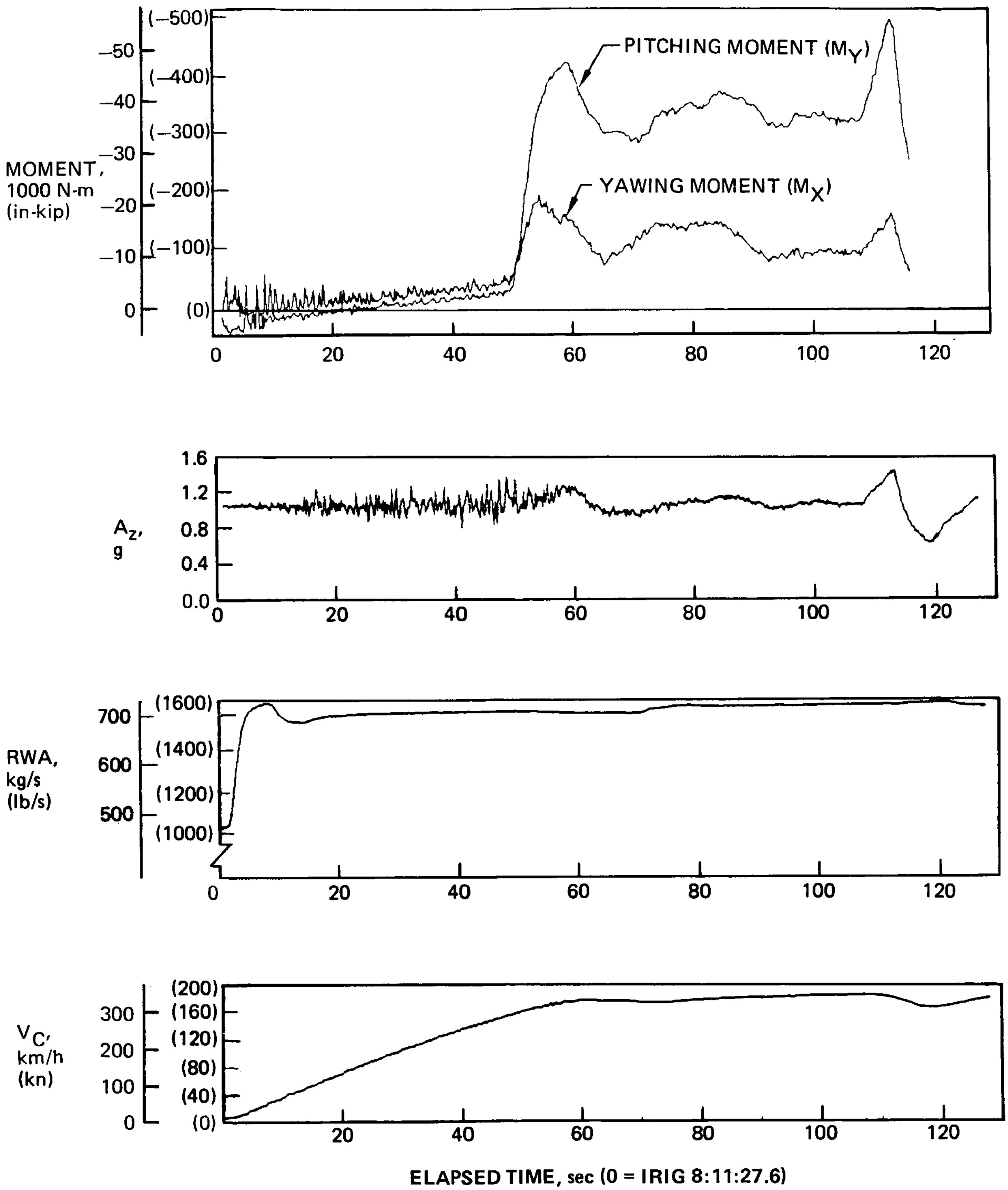

Figure 10. Time History of Takeoff and Condition 118 Pullup Maneuver

imposed by the other Boeing developmental programs was removed. Reference 6 contains complete tabulations of the IPSA pressure data. Because it was intended only to create a data base of surface static pressures from a full-scale aircraft, no analysis of the IPSA data was conducted.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

5.1.1 Management

The NAIL program was a highly successful one and had an unusual management structure: sponsorship by two different NASA research centers with execution by two distinct industrial organizations. Despite the apparent complexity of this arrangement, planned objectives were met or exceeded, on time and within budget.

5.1.2 Technical

The airloads measured in the takeoff phase of flight were higher than anticipated. Some other phases, specifically the stall warning maneuvers, generated less severe loads than those estimated in earlier analyses (ref. 4) because the flight techniques differed from those that had been assumed.

Inertial loads were less severe than previous studies had indicated.

Inlet angle of attack and engine airflow together determine inlet airloads. Inlet angle of attack can be influenced by the pilot through three parameters: flap setting, airspeed, and load factor (g). Airflow is determined by power setting. It may be possible to reduce operating airloads significantly by suitable revisions to flight procedures.

The airload data developed in the NAIL program will be applicable in nondimensional form to underwing high-bypass ratio turbofan installations involving airplane and engine combinations other than the JT9D-7/Boeing 747 combination.

A data base has been established that will permit evaluation and verification of improved analytical methods for studying aerodynamic interactions between wings and propulsion systems for turborfan-powered subsonic transport aircraft.

5.2 RECOMMENDATIONS

5.2.1 Management

The combined center management approach should be considered by NASA whenever the problem under investigation cuts across technology lines, as in this case, engine and airframe. However, the normal coordination procedures followed by industry should be allowed as was the case on the NAIL program.

5.2.2 Technical

It is suggested that modifications to flight procedures be considered with a view to reducing high-load occurrences in both test (acceptance flights) and airline service. In acceptance flights, recovery from stall warning maneuvers can result in lower load levels if engine thrust is not increased to maximum levels. (This is feasible because the altitude loss under those conditions is not a problem.) In airline service, use of a flaps 20 setting for takeoff and postponement of takeoff rotation to a higher speed will tend to reduce the maximum inlet angle of attack attained, resulting in significant airload reductions.

The loads data obtained in the NAIL program should now be used in formulating design criteria for engine-related structures to ensure minimum fuel-economy degradation from the start of the design process.

5.2.3 Future Work

More data are needed on the statistical aspects of engine loads. The NAIL program developed no information on the takeoff rotation speeds, flap setting selections, or rotation load factors normally encountered in airline service. Such data would be helpful in the use of the aerodynamic data gained by NAIL on subsequent design efforts. It is recommended that NASA develop a statistically significant takeoff operational data base as part of its continuing flight loads measurement program.

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16. Abstract

A flight test survey of pressures measured on wing, pylon, and nacelle surfaces and of the operating loads on Boeing 747/Pratt & Whitney JT9D-7A nacelles was made to provide information on airflow patterns surrounding the propulsion system installations and to clarify processes responsible for in-service deterioration of fuel economy.

Inlet airloads were measured by integration of pressures recorded at 252 locations on the right-hand inboard nacelle. Pressures were recorded at 45 locations on the right-hand outboard nacelle for comparison. Inertial loads were measured on both nacelles using accelerometers and rate gyros. Flight conditions included takeoffs at several gross weights, high-g turns, and a simulated acceptance flight.

Airloads at takeoff rotation were found to be larger than at any other normal service condition because of the combined effects of high angle of attack and high engine airflow. Inertial loads were smaller than previous estimates had indicated.

A procedure is given for estimating inlet airloads at low speeds and high angles of attack for any underwing high bypass ratio turbofan installation approximately resembling the one tested. Flight procedure modifications are suggested that may result in better fuel economy retention in service.

Pressures were recorded on the core cowls and pylons of both engine installations and on adjacent wing surfaces for use in development of computer codes for analysis of installed propulsion system aerodynamic drag interference effects.

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