

Design and Development of HondaJet

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ABSTRACT

Honda R&D has developed an advanced business jet. The HondaJet is an entry-level, light-weight, business jet featuring an extra large cabin, high fuel efficiency, and high cruise speed compared to existing small business jets. To achieve the performance goals, a natural-laminar-flow wing, a natural-laminar-flow fuselage nose, an over-the-wing engine-mount configuration, and other advanced technologies were developed. The wing is metal, having an integral machined skin to achieve a very smooth upper surface, which is required for natural laminar flow. The fuselage is made entirely of composites and the stiffened panels and the sandwich panels were co-cured integrally in an autoclave to reduce weight and cost. The advanced avionics system, which provides a high degree of integration for enhanced functionality and flight safety, was also installed in the cockpit. Several advanced technologies were employed for the HondaJet.

1. Introduction

Air transportation has seen an annual worldwide growth of 6.7% for the last 20 years, and the International Civil Aviation Organization (ICAO) estimates that it will continue growing at 5.3% per year for the coming 20 years. This represents a real increase with respect to the 3.3% growth predicted for the worldwide GDP during the same period. The market for business jets is expected to show the same trend; it averaged 8.1% growth during the last 20 years, and is projected to follow the course of GDP. There has been a renewed appreciation in recent years for the advantages of business jets over commercial travel (no waiting time at the ticket counter or for transfers to subsequent flights) and their safety (little exposure to hijackings or other terrorist acts). Interest in business jets has reached a pitch never before seen

in the market.

However, business jets are expensive, both in the purchase prices for the aircraft themselves and in operating costs, and have remained well out of reach of the average air traveler. Even for charter usage, fares are higher than those for first-class commercial tickets. This has been the biggest obstacle to the popularization of these aircraft. If prices and operating expenses can be brought down to allow fares comparable with airline tickets, it will bring about a dramatic change in the business jet industry.

The above conditions were motivations for the development of the HondaJet, which Honda believes will become the paradigm for the next generation of business jets. This report will present the design and testing of this jet, in the fields of aerodynamics, aeroelasticity, structure and systems.

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2. Overview of HondaJet and its Capabilities

Figure 1 shows an overall view of the twin-engine HondaJet. The power plant was developed by Honda. It is a highly efficient turbofan, designated HF-118. Each HF-118 develops a take-off thrust of 1 670 lb (7 428.5 N). It is a two-spool engine featuring Fully Automated Digital Engine Control (FADEC). The aircraft is a low-wing design with the engines mounted over the wing. The aircraft is 41.14 ft (12.5 m) long, has a wing span of 39.87 ft (12.2 m) and is 13.21 ft (4.1 m) high at the top of the T-tail. The design maximum take-off weight is about 9 200 lb (4 173 kg) and the maximum speed is about 420 kt (778 km/h) at 30 000 ft (9 100 m). This aircraft boasts about 10% greater speed and about 40% better fuel efficiency than other members of this class of business jets. The height inside the passenger cabin at the center aisle is 4.89 ft (1.49 m) and the length of the passenger cabin is 15.09 ft (4.6 m), offering a much larger passenger space than in other 4-seat planes. The passenger cabin is pressurized to 8.7 psi (60 kPa), to maintain 8 000 ft cabin altitude up to 44 000 ft.



Fig. 1 HondaJet

3. Aerodynamics

3.1. Wing

The aerodynamic design of the wing emphasized both good stall characteristics and minimum drag. A detail trade study was conducted to minimize both structural weight and induced drag. The study showed that the takeoff weight is minimized for a 1 100-nm-range aircraft when the wing geometric aspect ratio is 8.5 and a winglet having a height ratio of 9% is installed. An over-the-wing engine mount design was used for the HondaJet. This offers the advantages of minimum wave drag at high speed when the nacelle is in the optimized position and the maximum cabin volume⁽¹⁾. Since this is not a commonly used configuration, however, the stall characteristics were carefully studied by theoretical analysis and low-speed wind tunnel tests. Figure 2 shows the stall pattern observed on the wing, engine installed, of a 1/6-scale model in a low-speed wind tunnel test. Stall is initiated around 55% semi-span and spreads forward along the central portion of the wing. Thus, there is adequate stall margin over the outboard portion of the wing. Also, stall did not occur at the wing root area, between the engine and the fuselage, even

at angles initiating stall elsewhere on the wing. The over-the-wing engine configuration showed good stall characteristics. The low-speed wind tunnel tests showed similar results for the effect of the nacelle on lift characteristics; installation of the nacelle over the wing was proven not to disrupt the aerodynamic characteristics of the aircraft⁽²⁾.

Conformal mapping⁽³⁾ was used to develop a new natural laminar flow (NLF) airfoil designated SHM-1⁽⁴⁾ in order to accomplish the high performance goals for the HondaJet. The shape of the SHM-1 and typical pressure contours are shown in Fig. 3. The pressure gradient on the upper surface is favorable to about 42% chord, followed by a concave pressure recovery. This represents a balance between maximum lift, pitching moment, and drag divergence. The pressure gradient along the lower surface is favorable to about 63% chord, reducing drag. The leading edge (LE) shape was designed to promote transition near the LE at high angles of attack (AOA) in order to minimize loss from the maximum lift coefficient due to surface roughness. The trailing edge shape on the upper surface was designed to cause a very steep pressure gradient, with the intent of inducing a small separation. The new concept in trailing edge design allowed a large reduction in the wing pitching moment at high speeds.

In addition to the wind tunnel tests of this airfoil at low and transonic speeds, a T-33 trainer (Fig. 4) was equipped

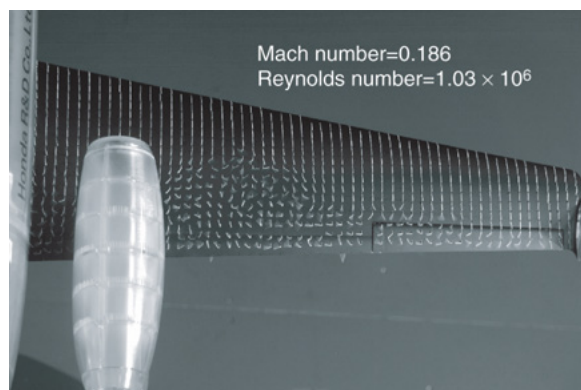


Fig. 2 Stall pattern

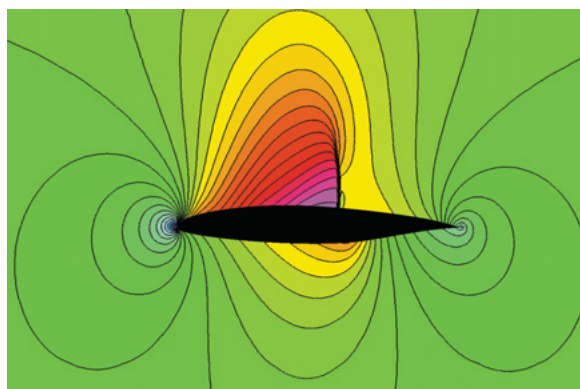


Fig. 3 SHM-1 airfoil shape and pressure contour

with a wing to confirm the performance of the airfoil at actual Reynolds numbers and Mach numbers. It was found to offer a low profile drag coefficient during cruise and climb, in addition to its high maximum lift coefficient and docile stall characteristics.



Fig. 4 T-33 aircraft modified for NLF flight test

3.2. Over-the-wing Engine Mount Configuration

The major design decision was that of engine location. Many technical parameters were examined in studies to compare the proposed over-the-wing engine mount configuration with that of the standard rear-fuselage engine mount. In general, locating the engine nacelles over the wing has potential to cause unfavorable aerodynamic interference and induces a strong shock wave, lowering the drag-divergence Mach number.

Theoretical studies were conducted using a three-dimensional Euler solver⁽⁵⁾; next, transonic wind tunnel tests were conducted in the Boeing Transonic Wind Tunnel to validate the theoretical predictions (Fig. 5). An optimum position for the nacelle relative to the wing was identified to minimize the shock wave, and drag divergence was found to occur at a Mach number higher than that for the clean-wing configuration. Favorable interference is obtained when the forward end of the nacelle is located near the position of the shock wave of a clean wing and the vertical distance between the wing upper surface and the nacelle lower surface is



Fig. 5 Transonic wind tunnel test

between one-third and one-half the maximum height of the nacelle above the upper wing surface; this results in a lower drag than the conventional rear-fuselage engine mount configuration⁽¹⁾.

The final configuration for this aircraft was determined by the above results. The over-the-wing engine mount configuration offers cruise performance superior to that of the rear-fuselage engine mount configuration and the largest cabin volume of any business jet in its class.

3.3. Flaps

In addition to the required high-speed capabilities, in order to obtain the required stall speed, the aircraft employs a linkage-type, double-slotted 30% chord flap. The two-dimensional multiple-element panel code MCARFA⁽⁶⁾ and the two-dimensional multiple-element Euler code MSES⁽⁷⁾ were used to design the shapes, gaps, overlaps, and other characteristics of the vanes and flaps. These designs were then tested in the Honda low-speed wind tunnel using the 1/6-scale model and the 1/3-scale half-model (Fig. 6). The results of these tests at two Reynolds numbers were combined with the pressure-difference rule⁽⁸⁾ to analyze the design, providing a quite accurate prediction of the maximum lift coefficient for this aircraft. The maximum lift coefficient was estimated to be about 2.5 in the full scale aircraft and the flap configuration was proven to meet the target stall speed.



Fig. 6 1/3-scale low-speed wind tunnel model

3.4. Engine Simulations

It is essential to minimize distortions in the flow into the engines above the wing during flight at high AOA. Low-speed powered-model wind tunnel tests were conducted using the 1/6-scale model (Fig. 7).

Forty total-pressure probes were installed on the plane of rotation of the fan to observe the flow pattern, and static pressure ports were drilled along the inlet duct to measure separation at the lip. The pitch and yaw of the fuselage, airspeed and engine fan speed were systematically varied and the combined effects of these on the complete distribution of pressure in the air inlet were studied. Four AOA (10°, 15°, 18° and 26°) and three yaw angles (−18°, 0° and 18°) were employed with a mass-flow ratio of 1.15, which corresponds to the condition of approach speed with required thrust. An example of the results is shown in Fig. 8.

The inlet total-pressure distortion was less than 0.1% up to the stall AOA of 15° , then within 2% from stall up to the 26° . Similar results were obtained from tests with mass-flow ratios of 0.65 and 2.15. The tests with the high mass-flow ratio of 2.15 showed low total-pressure distortion at all AOA; the tests with the low mass-flow ratio of 0.65, corresponding to the cruise condition, showed slightly higher distortion at AOA higher than stall. These results demonstrated that the distortion does not exceed the limits specified by engine requirements in the flight envelope.

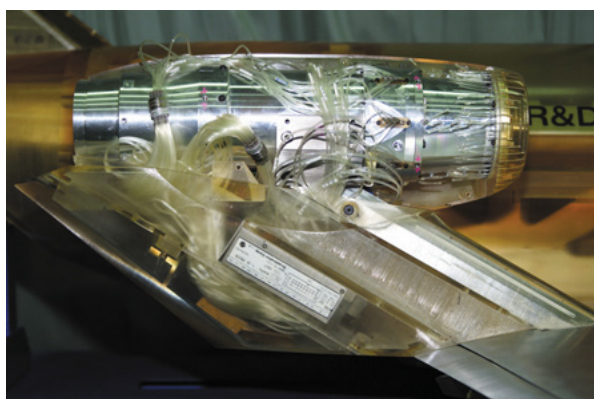


Fig. 7 1/6-scale engine simulator

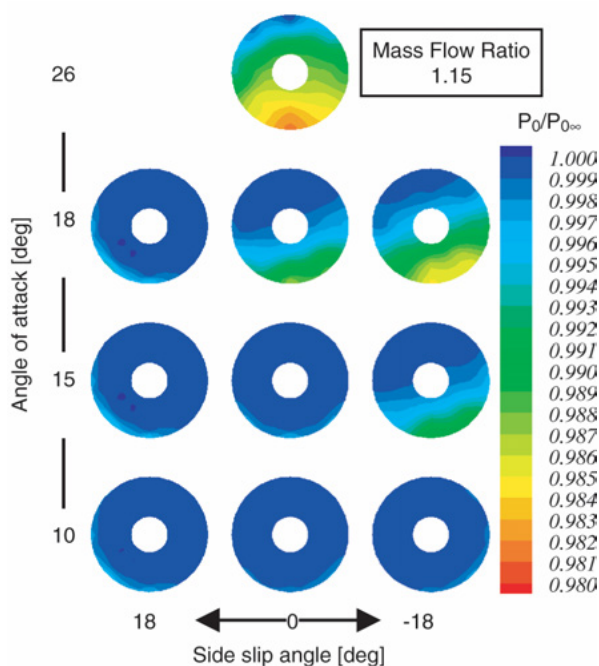


Fig. 8 Pressure distribution pattern obtained from powered model test

3.5. Laminar Flow Nose

A new NLF nose shape was designed in order to reduce fuselage drag. A three-dimensional panel code and an integral boundary-layer method were used⁽⁹⁾. The exterior shape of the nose is designed both to maintain a favorable pressure gradient and to minimize crossflow, in order to maximize the length of the laminar flow region. A 1/3-scale model of the fuselage was constructed to verify this shape by testing in Honda's low-speed wind tunnel (Fig. 9). Infrared cameras were also used to visualize the flow on the nose at each AOA (Fig. 10).

The results show that extensive laminar flow is achieved at climb and cruise AOA. Since steps and gaps are detrimental to the achievement of NLF, various steps and gaps were installed on the nose to determine the critical sizes. A NLF nose reduces fuselage drag about 10% compare to that of a fuselage with a turbulent-flow nose (Fig. 10).



Fig. 9 1/3-scale fuselage model for NLF nose test

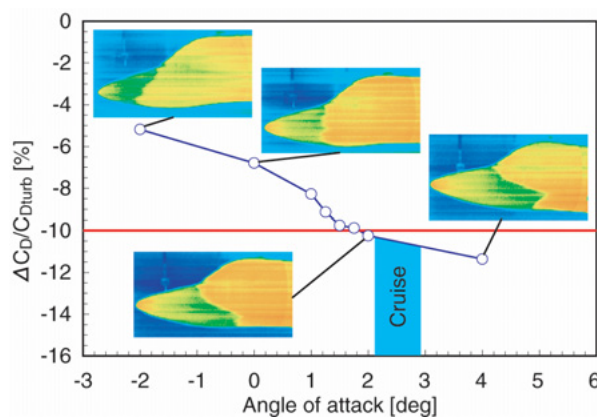


Fig. 10 Drag reduction of NLF nose

3.6. Low-speed Wind Tunnel Testing for Stability

Extensive, six-component force wind tunnel tests were conducted to obtain the aerodynamic characteristics and the stability derivatives. Two wind tunnels, the Honda low-speed wind tunnel (Fig. 11) and the University of Washington low-speed wind tunnel, were used. The stability derivatives obtained from these tests were used to simulate the aircraft flight characteristics using the Honda six-degree-of-freedom flight simulator (Fig. 12). It was verified that the flight characteristics satisfied the MIL-8785C and other standards.verified that the flight characteristics satisfied the MIL-8785C and other standards.

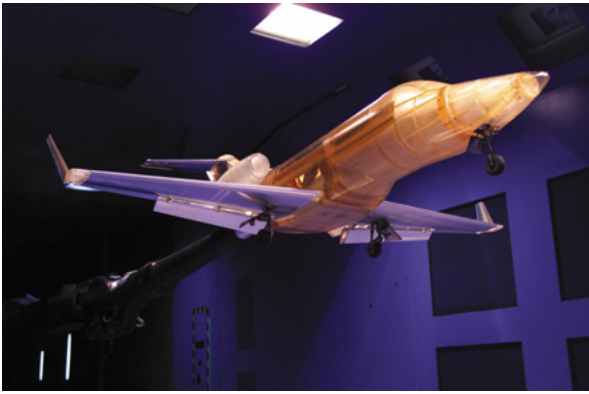


Fig. 11 1/6-scale wind tunnel

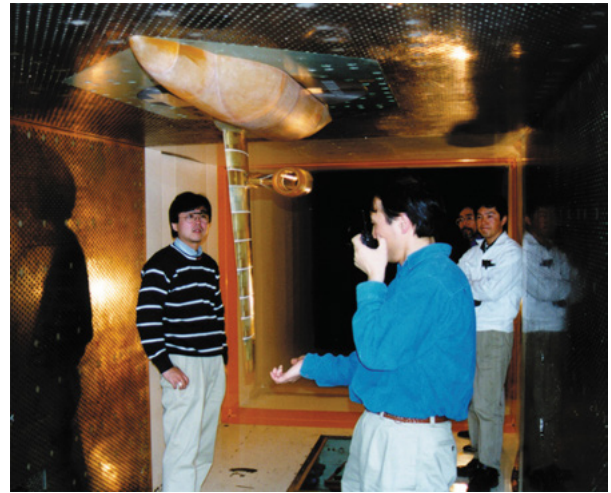


Fig. 13 Transonic wind tunnel flutter test at JAXA transonic wind tunnel



Fig. 12 Honda flight simulator(HNAFS)

4. Aeroelasticity

4.1. Over-the-wing Engine Configuration

Mounting the engines on the wing causes complex wing-flutter characteristics. The location of the engine mass, its relation to the wing, and the relation of the pylon stiffness to the wing stiffness are important for flutter characteristics. To investigate these characteristics, theoretical analyses were performed using the ERIN code and low-speed and transonic wind tunnel flutter tests were conducted at the Japan Aerospace Exploration Agency (JAXA) Transonic Flutter Wind Tunnel (Fig. 13).

For the over-the-wing engine mount configuration, the symmetric flutter mode occurred at a lower speed than the anti-symmetric flutter mode. It was also verified that the effects of the aerodynamic load and the interference due to the engine-nacelle installation over the wing are small at transonic speeds. The vibratory characteristics of the engine pylons were found to affect flutter characteristics. For example, the flutter speed was highest when the engine-eylon side-bending frequency is close to the uncoupled 1st wing-torsion frequency (about 0.9 – 1.0 times the uncoupled 1st wing-torsion frequency) and lowest when the engine-eylon pitching frequency is about 1.25 times the uncoupled 1st wing-bending frequency⁽¹⁰⁾.

The wing stiffness and mass distribution were designed based on these results to satisfy the flutter-clearance requirements.

5. Structure

5.1. Wing

The wing is constructed in three sections, left outboard wing, center section, and right outboard wing (Fig. 14). Its structure consists of an aluminum spar and aluminum skin. The torque-box structure consists of three spars, ribs and skin with integrated stringers forming an integral fuel tank.

The skin of the upper surface, made of A7050 aluminum plate, is machined, integral panel to maintain the contour required for laminar flow. This configuration allows the most efficient distribution of material and the lowest number of parts.

The LE structure and the main torque-box structure are mated at 13.5% chord to reduce the disturbance to the laminar flow. The LE contains a piccolo tube (a tube with lines of holes) which directs hot engine bleed air against the inside surface of the LE skin for de-icing.

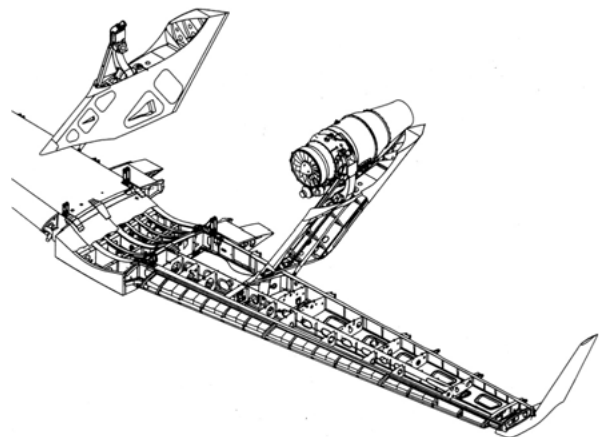


Fig. 14 Wing structure

The pylon structure is attached with four bolts to a reinforced, Y-shaped rib. The main landing gear is attached to the inboard side of the reinforced rib. The design introduces the heaviest loads on this aircraft structure into the same locations. The vertical loads from the wing are carried forward and aft into the fuselage main frame by four links, while the lateral loads are transmitted through V-shaped links left of those links. Forward-aft loads are transmitted to the fuselage by two thrust rods.

The wing structural design was substantiated by a proof test. The MTS Aero-90 test system was used with a total of 26 computer-controlled hydraulic actuators to simulate airloads, engine thrust and landing gear loads. Over 600 channels of data (strain, displacement, force, etc.) were measured during each test case. The actual number of cases studied, out of the 870 cases, was 10. These were pylon vertical load, pylon side load, flap load, Vc positive gust, Vc negative gust, right and left one-gear landing conditions, level landing with spin-up load, crabbed landing, and rudder maneuver.

Since the same wing structure used for proof tests will also be used for flight testing, the test loads were limited to 80% of the limit loads (Fig. 15). The measured strain, displacement, and reaction-force data were compared with those from a finite element analysis and the results were extrapolated to estimate the limit-load values.



Fig. 15 Wing proof test

5.2. Fuselage

The fuselage structure is made of composites. The material is a 180 °C cure epoxy prepreg reinforced with carbon fiber. (The matrix is Cytec 5276-1 high-damage tolerance epoxy resin and the fiber is TOHO G30-500 high-strength, intermediate modulus fiber⁽¹¹⁾.)

As shown in Fig. 16, the cockpit and the tail section is a honeycomb sandwich construction to maintain the compound curves that are required for the laminar-flow nose. An integrally stiffened panel structure is employed for the constant cross section portion of the cabin, which maximizes the cabin volume. Identical frames and stringers are used for the constant section of the fuselage to simplify fabrication. The constant fuselage section can easily be stretched in future models.

A major feature of the fuselage is that the sandwich panel and the stiffened panel are co-cured integrally in an autoclave to reduce weight and cost. It was a technical challenge to cure the honeycomb sandwich structure under the pressure (0.6 MPa) required for the stiffened panel. The ends of the workpiece were stabilized in picture-frame jigs, which prevented crushing of the honeycomb core.

The windshields are shaped in compound curves for good aerodynamic characteristics. They are constructed of two plies (inner and outer) of stretched acrylic with a polyurethane interlayer, which has superior low-temperature ductility, a higher allowable operating temperature, and higher adhesive properties. The exterior surface of the outer acrylic ply and the interior surface of the inner acrylic ply are hard-coated for abrasion and chemical resistance. The windshield has an electric de-icing system. The windshield and its supporting structure are designed to withstand the impact of a 4-lb (1.8-kg) bird strike at Vc at sea level.

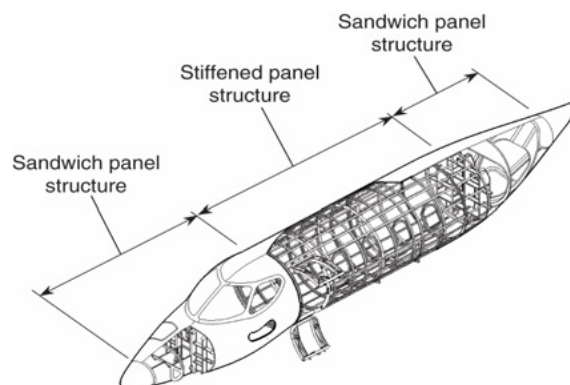


Fig. 16 Fuselage structure



Fig. 17 Fuselage proof test

The fuselage structural design was substantiated by a proof test (Fig. 17). Six computer-controlled hydraulic actuators were used to simulate loads, including that from pressurization. A total of six load cases were observed: pressurization, positive gust, positive gust with pressurization, rudder maneuver, rudder maneuver with pressurization, and two-point landing. As in the wing structure tests, the same fuselage used for proof tests will also be used for flight testing, so the test loads were limited to 80% of the limit loads. The fuselage strength was verified by the same method as the wing strength.

6. Systems

6.1. Landing Gear

The landing gear is a typical tricycle configuration with a steerable nose wheel. The main gear is the trailing-link type (Fig. 18) and the retraction actuator is the side brace. The landing gear doors consist of three doors, inboard, middle and outboard. The inboard door is operated with its own hydraulic actuator and the middle and outboard doors are operated by the movement of the gear through a linkage with the landing gear strut. The wheel well is completely covered by the doors so that the wheels are unexposed to the airstream and minimizes drag during cruise. The side brace actuator is equipped with an internal down-lock mechanism; in an emergency, a dump-valve allows free-fall extension of the gear.

The main gear contains an anti-lock braking system; it was tested on a dynamo system to optimize brake control. The braking system is fully equipped with locked wheel protection, touch-down protection, and spin-up override.

The nose gear incorporates a shock-absorber strut (operating in the vertical direction). The drag brace actuator retracts the gear forward (Fig. 19). The doors are operated by a linkage with the gear as the gear is extended or retracted. The drag brace actuator is equipped with an internal down-lock mechanism. The nose gear features steer-by-wire through hydraulic actuators controlled by pulse-width modulation (PWM). There are two modes for the steering

system: taxi mode, in which the steer-angle range is $\pm 50^\circ$, and takeoff mode, in which the range is just $\pm 10^\circ$. The nose gear also incorporates an accumulator for emergency control of steering in case of hydraulic pump failure.

Drop tests of the shock absorption characteristics of the gear were conducted using a weight to simulate aircraft mass (Fig. 20). The oleo shock absorber was found to satisfy the design objectives.

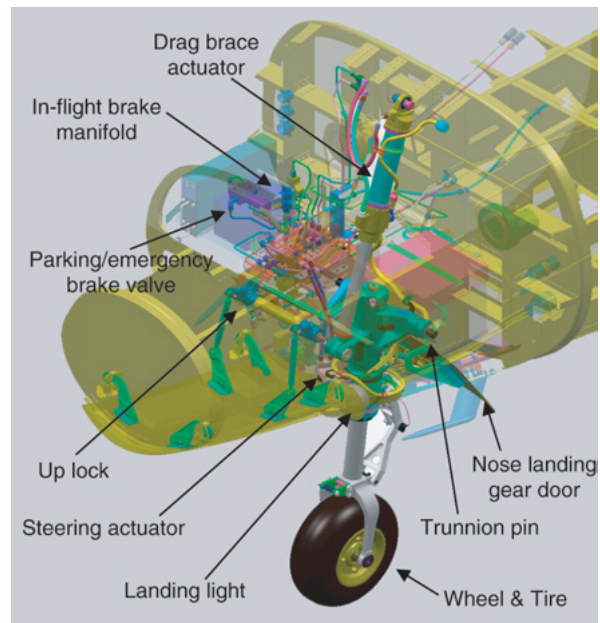


Fig. 19 Nose landing gear

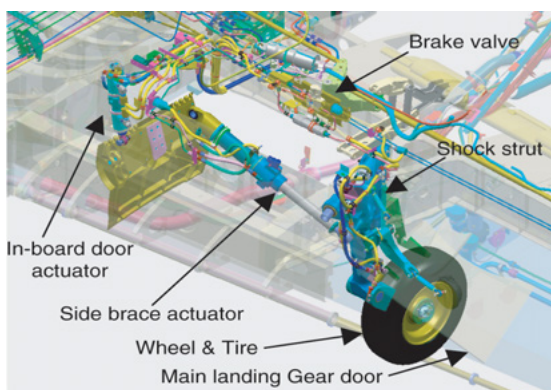


Fig. 18 Main landing gear

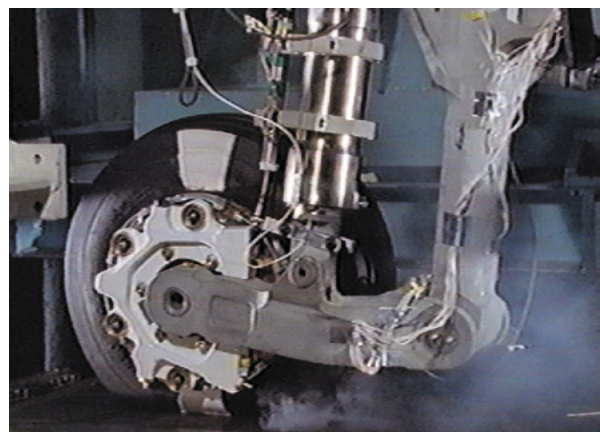


Fig. 20 Main landing gear drop test

6.2. Flaps

This aircraft employs a mechanically extended, linkage-type flap with a fixed vane. As shown in Fig. 21, there are two extended positions, 15.7° for takeoff and 50° for landing. The flaps are driven by two hydraulic actuators, one at the root of each wing, and are mechanically interconnected to prevent a split condition (differing extension angles between left and right sides).

A fatigue test was conducted under flight load conditions. Airloads were simulated using a hydraulically loaded whiffle tree, which allowed the flaps to move. The results indicated that the flap mechanism withstands the number of fatigue cycles required for the flight tests program.

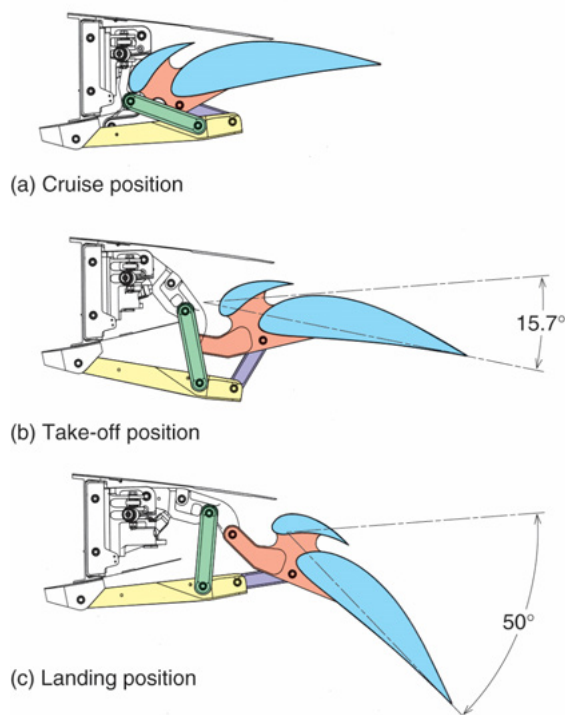


Fig. 21 Flap linkage mechanism

6.3. Fuel System

As shown in Fig. 22, the HondaJet has four fuel tanks, a carry-through tank, left-wing internal tank, right-wing internal tank, and rear-fuselage bladder tank.

Refueling is done through a single supply point on the right side of the rear fuselage. Fuel is transferred by two transfer pumps from the carry-through tank to the internal tanks in both wings. It is supplied to the right engine from the right-wing tank, and to the left engine from the left-wing tank, via collector tanks beneath each engine pylon. The primary pumps are ejector-type units and electric boost pumps are used during engine starting. A fuel transfer management unit (FTMU) maintains the fuel level in the wings, reducing mean wing root bending moment by about 12%. An automated cross-feed function system is also provided in order to allow both asymmetric thrust condition and correction of imbalance. The unusable fuel quantity was reduced to about 2% of total volume.

There are a total of 13 capacitance-type fuel sensors in the fuel system, three in the carry-through tank, four in each wing tank, and two in the bladder tank. They measure the amount of fuel with an accuracy of 2% + 1% of full-scale during any flight conditions within the aircraft's flight envelope.

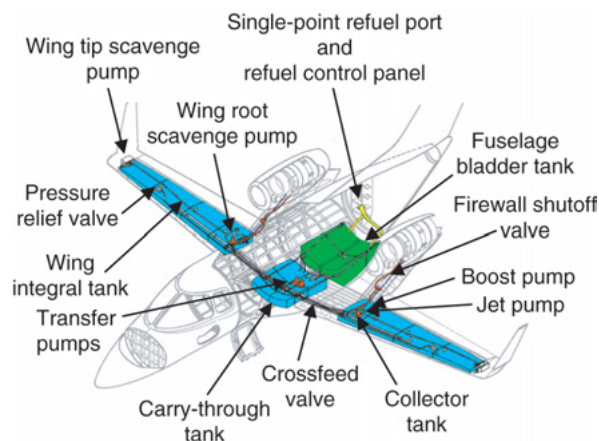


Fig. 22 Fuel system

6.4. Avionics

The HondaJet employs an all-glass flightdeck featuring modular design having open architecture. Figure 23 shows the cockpit. All data, such as aircraft attitude, air data, engine conditions, meteorological data, traffic conditions and geography, are digitally represented on two primary flight displays (PFD) and one multi-function display (MFD). The PFD contains an airspeed indicator, vertical-speed indicator, adjustable altimeter, direction indicator, pitch and bank indicator (artificial horizon), slip/skid indicator, dual NAV/COM and other functions. The MFD contains the EIDS (N1, ITT, N2, oil temperature, oil pressure), fuel flow, fuel quantity, generator current, GPS map, and other information.

Thus, the cockpit of the HondaJet incorporates highly integrated aircraft management capabilities for enhanced situational awareness, functionality, easy operation, redundancy, and flight safety.



Fig. 23 Cockpit

6.5. Other Systems

In order to maximize the volume of the cabin, the systems of the HondaJet were laid out as follows to make the most effective use of space in the nose compartment, wing-fuselage fairings, pylons and behind the rear bulkhead. The nose compartment contains the batteries, parking brake valves, the Attitude and Heading Reference System (AHRS), and other components. The wing-fuselage fairing holds Environmental Control System (ECS) tubing, heat exchangers, flow control valves, trim valves and other related equipment. In each pylon are fire control equipment and pre-coolers. In the aft section are the DC motor pumps (DCMP), reservoirs, accumulators, air conditioning, and related equipment. Figure 24 shows the locations of the systems. This new layout has allowed the designers to create an effective cabin volume which far exceeds that of other planes in this class.

7. Conclusion

Honda has developed and successfully flown a light, advanced business-class aircraft. It boasts many innovative features, including over-the-wing engine mount, natural laminar flow wings, natural laminar flow nose, and composite fuselage, which enable the HondaJet to offer a larger cabin volume, higher speed and greater fuel efficiency than any other jet in its class. The capabilities of this jet will be verified in extensive flight-testing. The author thanks everyone inside and outside Honda who have shared in this dream and contributed to its realization.

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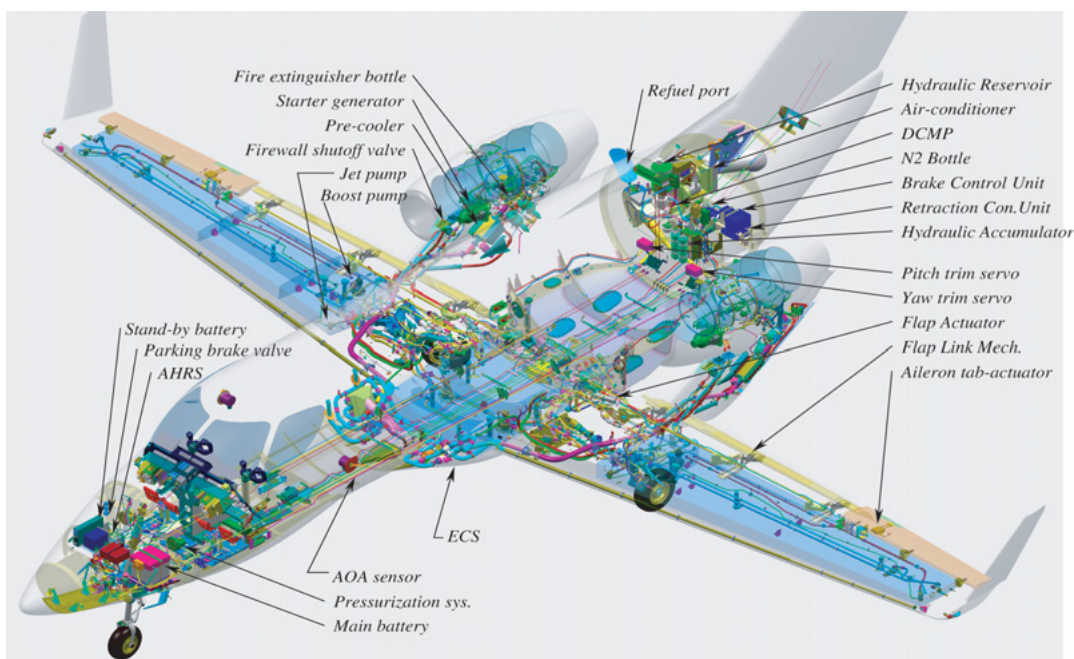


Fig. 24 System layout

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