QUIET STOL RESEARCH AIRCRAFT ASUKA - DEVELOPMENT AND FLIGHT TEST

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Abstract

This paper presents the development and flight test results of the Japanese research project on the fan jet QSTOL (Quiet Short Take-Off and Landing) aircraft, "ASUKA" by the National Aerospace Laboratory (NAL).

The QSTOL research aircraft "ASUKA" is designed to perform research on powered lift technology and STOL operation, which has four high bypass ratio turbofan engines on the wing for Upper Surface Blowing type high lift device, Boundary Layer Control system on leading edge of wings and ailerons, the Stability and Control Augmentation System with triplex redundant digital computers, a Head Up Display for precise STOL approach and so on.

The flight test of ASUKA was conducted from October, 1985 to March, 1989. ASUKA flew about 170 hours and 97 flights. During its flight tests, aerodynamic performance of the high lift device and control techniques for STOL approach and landing were major two items to be investigated.

Some selected data are presented with explanation of flight tests. Finally, some problems of airworthiness criteria for civil STOL transport aircraft are discussed.

Introduction

Figure 1 shows the NAL STOL-1 "ASUKA" flying over Shima peninsula in the central part of Japan.

The history

Figure 2 shows the master schedule of QSTOL research program. The Science and Technology Agency (STA) initiated a three-years feasibility study about the Quiet Short Take-Off and Landing (QSTOL) research aircraft in 1972. It was the first step of the National Aerospace Laboratory (NAL)'s QSTOL Aircraft research Project which has been started in 1977.

Figure 1. NAL QSTOL Research aircraft "ASUKA" flying over Shima Peninsula.

In 1970s, air travel became more popular and convenient with the second generation jet airliner, but on the other hand, environmental problems, such as noise and air traffic congestion etc., became more serious especially in Japan. Based on the study, the STA advisory committee recommended to develop and establish the technology for a QSTOL airplane, and the recommendation included to build the research aircraft and conduct the flight experiment with it by NAL.

After the preliminary design competition, the Kawasaki C-1 tactical transport aircraft has been selected as a base aircraft to be modified to QSTOL research aircraft, and newly designed and developed high bypass ratio fan jet engine, MITI (the Ministry of International Trade and Industry) /NAL FJR710/600S, has been chosen as the engines for the research

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aircraft.

NAL organized a design team for the aircraft in collaboration with Kawasaki Heavy Industries Ltd. and other main Japanese aircraft manufacturers in 1977.

As in Figure 2, the design work was started in 1977, final assembly was started in 1982, and the roll out was in March 1985. Following the ground functional test, the flight test was started with the first flight on October 28, 1985. And all of the flight test schedule was completed in 1989. The flight test data analysis and the study to establish the design criteria for STOL transport aircraft are still continuing by NAL.

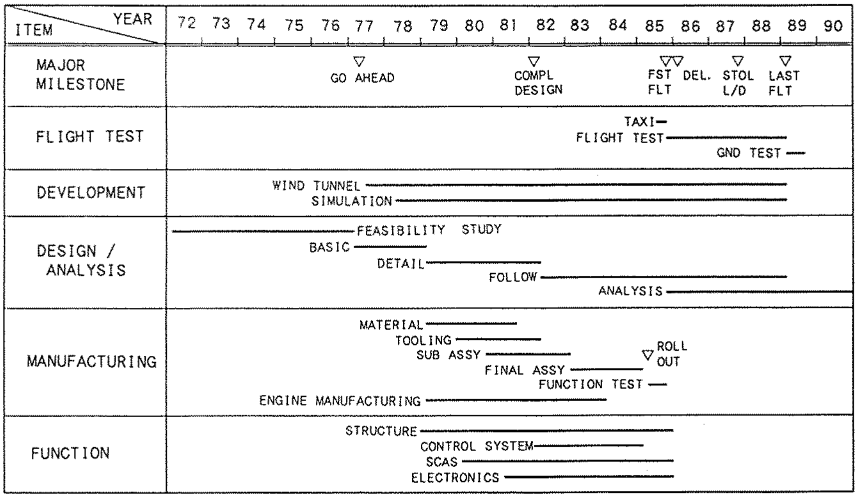

Figure 2. Master Schedule of the QSTOL Research Program

Design goal

The subjects of this QSTOL research project (ASUKA project) are set as follows;

- to prove the STOL ability with powered lift technology,
- to examine and establish the design criteria for STOL flying quality,
- to acquire the data for a powered lift STOL transport aircraft.

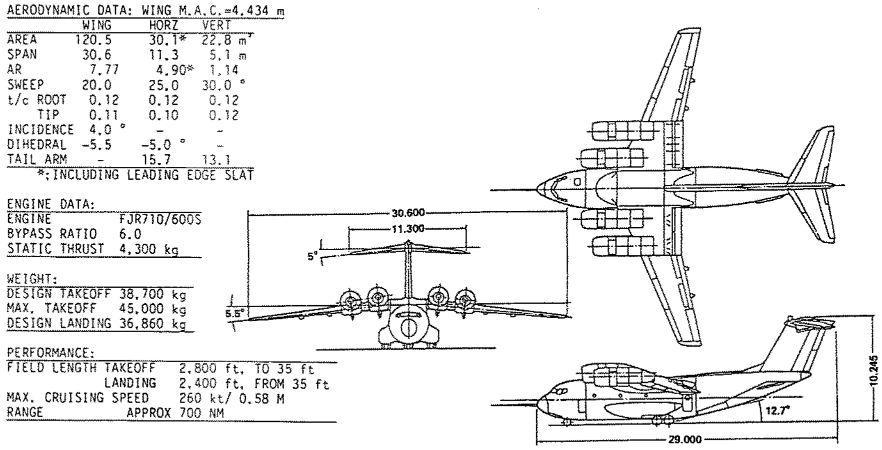

Figure 3. Three View Drawing of "ASUKA"

ASUKA should have enough high lift performance for flight test to realize these subjects. We set the design goal instead of the firm requirement as shown in Table 1.

TABLE 1. THE NAL QSTOL "ASUKA" PERFORMANCE DESIGN GOAL

ITEM	GOAL	NOTE
FOR STOL:		
REF. APPROACH AIRSPEED	72 KT	at max. landing weight
REF. FLIGHT PATH ANGLE FOR APPROACH	-6 °	at max. landing weight
REQUIRED FIELD LENGTH	< 3,000FT*	at max. takeoff or landing weight, sea level, ISA, dry runway
* for landing length from 35ft height devided by 0.6, for takeoff balanced field length over 35ft		
MAX. CRUISING AIRSPEED	> 0.5 MACH	at max. STOL takeoff weight altitude of 25,000-30,000ft, at ISA

Outline of the "ASUKA"

Figure 3 shows a three-view drawing of the NAL QSTOL "ASUKA" with some data.

Technological features,

The "ASUKA" provides many technological features as shown in Figure 4, they are;

- Upper Surface Blowing (USB) flaps,
- Boundary Layer Control(BLC) system,
- Stability and Control Augmentation System,
- flight control system with triplex hydromechanical series servo actuator,
- heat resist composite material of wing surface,
- sonic abatement techniques,
- newly developed high bypass ratio fan jet engine with much bleed air, etc.

Those technical features are thoroughly confirmed through research or developmental tests, while original part of the basic airframe are considered reliable enough without any tests. And after completion of assembly the aircraft, the ground functional tests including the ground vibration test were conducted before the first flight.

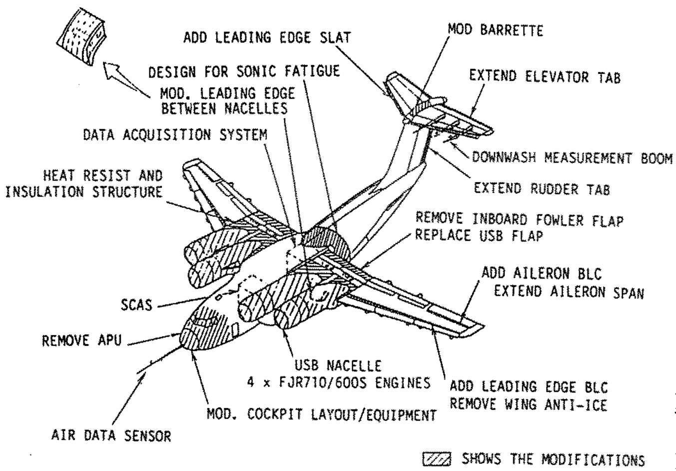

Figure 4. The Modifications of "ASUKA".

Design and development

Some additional explanations and topics during design and development phase on them are discussed here.

Aerodynamic design

At the beginning, a wind tunnel test was a only way to get the design information, because there were almost no data and usual analytical way to design a USB type powered lift aircraft. Numerous hours of wind tunnel tests have been done from 1975, and still been continued. The total wind tunnel test days were counted 540 days, and total hours of wind blow were 1,650 hours from 1975 to 1981, when the design phase was finished.

There are four main models for the wind tunnel tests, one is a 8% full span model for force and moment measurement at low airspeed, and three semi-span models, one of them is a 8% model for aerodynamic shape refinement, one is a 8% model for the pressure distribution and hinge-moment measurement, and the last is a 7% model for high speed wind tunnel tests. And to determine the detail, the component model wind tunnel tests were done such as the vertical tail, horizontal tail, engine intake and the drill hole type BLC model.

The aerodynamic characteristics of a powered lift aircraft like ASUKA are greatly influenced by engine power with jet effect and interference. So that it is very important to investigate the powered model wind tunnel tests. The simulated fan engine, driven by high pressure cold air turbine is used for our wind tunnel tests. The BLC system on leading edge of wings and ailerons is also simulated except a type of air outlets, ASUKA uses a drill hole type but the model is a slit type. It is very difficult to eliminate the interference force and moment with an air supply duct from the wind tunnel balance system. A special air joint is used to minimize the interference, and the static tear test is done to compensate the interference at every period of the tests.

The ground effect and the flow field at the tail (downwash) were also measured in the wind tunnel.

Flying quality

To attain the Short Take-Off and Landing performance, an aircraft should fly at very low airspeed, it means to fly at the high lift coefficient, CL, and it requires powered high lift devices. To fly with powered lift devices, the flying qualities become much different from a Conventional Take Off and Landing (CTOL) aircraft about the following items;

- large pitching moment change with power,
- decreasing heave damping, Zw,
- strong backside power required curve,
- longitudinal long term characteristics becomes less stable,
- dutch roll and spiral characteristics becomes worse,
- decreasing roll power,
- large rolling moment change at the event of engine failure, and so on.

The Stability and Control Augmentation System (SCAS) has designed to improve these flying quality. Figure 5 shows the simplified block diagram of the SCAS.

Flight simulation, The flight simulation test with pilots has been utilized widely to check and to develop the SCAS and the flying quality, as well as to confirm the performance. The failure or disturbed conditions, such as turbulence, gust, wind shear, engine failure, malfunction of the flight control system including the SCAS and so on, are also examined and evaluated. The simulation tests were started in 1978, it was a very early design phase, and the control technique during STOL approach was determined as the STOL control technique at this early tests. The STOL technique means that to control flight path with power, and to control airspeed with pitch attitude. On the contrary, the CTOL technique means to control flight path with pitch attitude, and to control airspeed with power. The basic construction of the SCAS loop was settled by this choice.

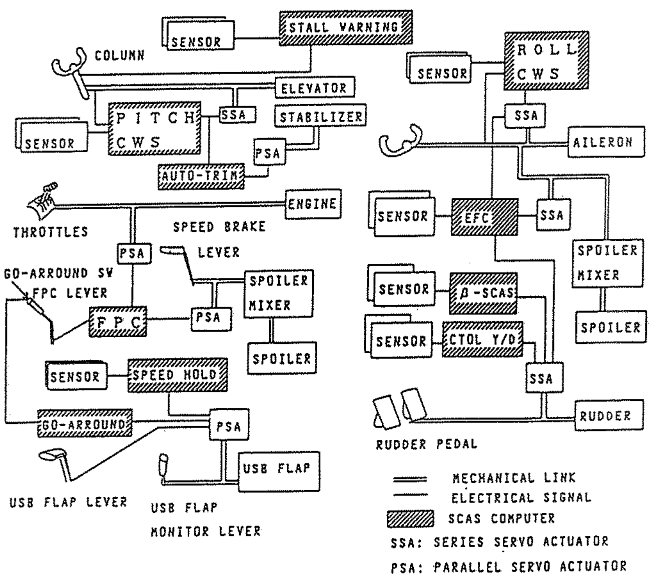

Figure 5. The SCAS Basic Block Diagram,

Structure

There are three major problems for the structural design of ASUKA. One is a USB flap design to support the high lift, one is heat resist and thermal insulation design, and the last is the design for the sonic fatigue.

USB flap, Figure 6 shows the schema of the USB flap, this flap is consisted of two surfaces, fore and main and hinge type support with hydraulic actuator. The beam is mainly made of titanium alloy (Ti-6Al-4V) and trailing edge is made of honeycomb sandwich structure of glass/polyimide composite material to resist thermal and sonic pressure of high temperature engine exhaust.

Glass/polyimide heat resist composite material, USB type high lift devices require the heat resist and insulation against high temperature and high level of sonic pressure on wing surface and USB flap. The design temperature was set to 200 °C, and polyimide resin group of the composite material was found suitable for our purpose. On the wing surface two stage honeycomb sandwich panels are attached to the surface by bolts and silicon adhesive.

Design for the sonic fatigue, The wing, USB flap and aft fuselage are exposed to the high temperature exhaust and high level of sonic pressure. The requirement of safe life of the Federal Aviation Regulations (FAR) part 25 is used as the design requirement. Required service life is set as 750 flights according to the Miner's accumulated damage rule.

USB flap and engine nacelle were tested at the component test to confirm the design.

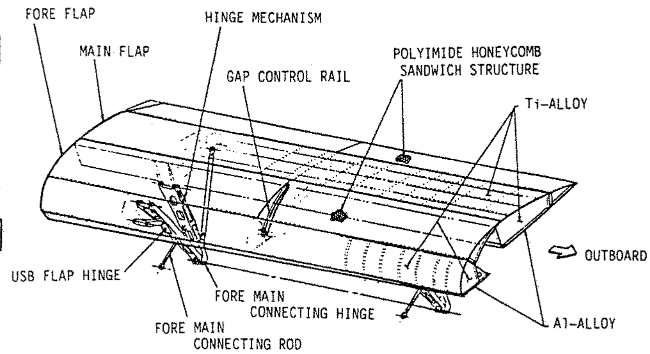

Figure 6. The Outline of USB Flap Structure,

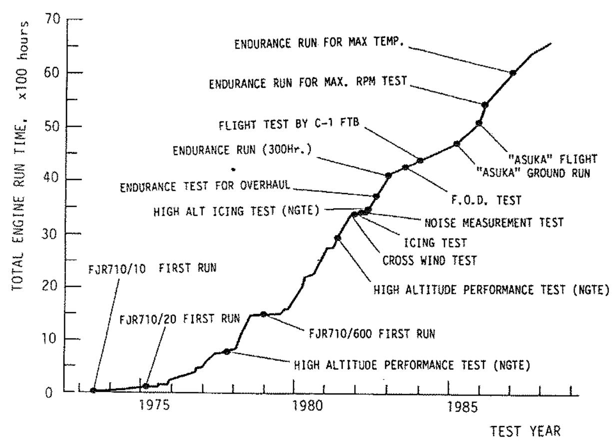

Figure 7. The FJR710 Engine Run History,

Engine development

The MITI/NAL FJR710/600S engine has developed by the consortium of Japanese aero engine manufacturers under the fund of the National Research and Development Program of MITI and NAL from 1971. Figure 7 shows the record of engine test run and test item. As shown in Figure 7, various tests were executed to prove the airworthiness and to obtain the assured performance and maintenance data. And finally the engine has been operated more than 6,600 hours including ASUKA flight.

The environmental tests such as foreign object damage tests, icing tests on ground and high altitude, inlet distortion tests in turbulent air and cross wind, etc. were also conducted. The icing tests at high altitude were done at the Royal Aerospace Establishment (the National Gas Turbine Establishment) in Great Britain.

The engine flight test using the Kawasaki C-1 flying test bed was done totally 25 flights to confirm the engine behavior in flight by the JSDAF (Japan Self Defense Air Force) in 1984. Figure 8 shows the test points and items in this flight test.

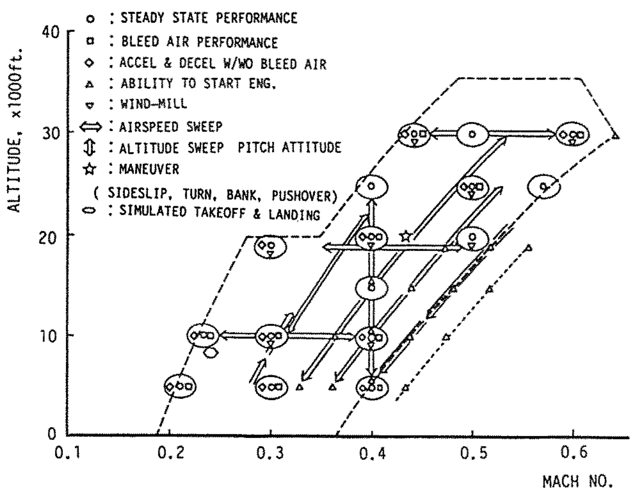

Figure 8. FJR710/600S Engine Test Points by the C-1 Flying Test Bed,

The flight tests

The flight tests were conducted at the Gifu airfield and in the flight test area about 90km (50nm) south from the field, as shown in Figure 9. There is the NAL flight test center and the aircraft manufacturing plant of the Kawasaki Heavy Industries and the JSDAF base at Gifu airfield. At the flight test center, flight tests can be monitored and controlled by the engineer, data acquisition system including tracking radar is fully equipped. The PAPI (Precision Approach Path Indicator) is provided at the end of the runway to assist pilots tracking the precise steep gradient approach flight path. Figure 10 shows the outline of the monitor and analysis system.

Topics of the flight tests

Overview, Figure 11 presents the overview of the flight tests, it consists of the company flight and NAL flight, the entire flight tests was divided to the phase 0 and phase 1 flight. ASUKA flew totally 97 flights, 167 hours 10 minutes by the end of March 1989. In the company flight, basic function and safety was confirmed by mainly qualitative data. After delivered to NAL, the phase 0 flight mainly devoted to confirm the design and function of the system, and then STOL takeoff and landing were carried out, and demonstrated the field length of 509m (1670 ft.) for takeoff and 449m (1473 ft.) for landing, both data are over 10.7m (35 ft.) obstacle.

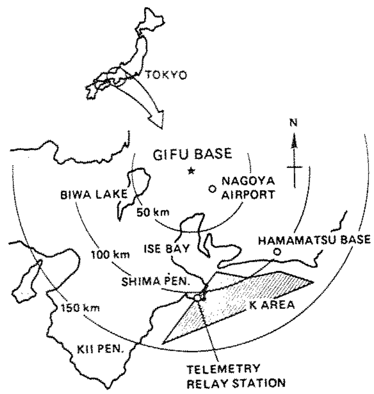

Figure 9. Base and the Flight test area,

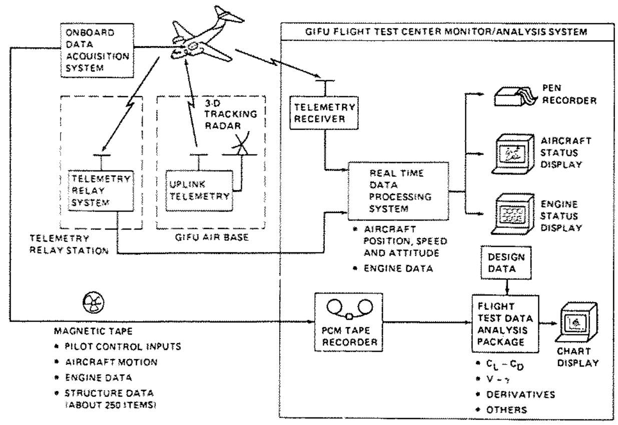

Figure 10. Monitor and data acquisition system,

During the phase 1 flight, besides the quantitative data acquisition, many programs were examined.
Major items of them were;

- optimization of the configuration i.e. slats and flap combination,
- modification between engine nacelles to alleviate the buffet,
- improvement of the flight path control,
- measurement of the downwash at the horizontal tail,
- measurement of the pressure distribution on the wing,
- guest pilot program, evaluation by

NASA pilots, and so on.

Some interesting flight test results are described here.

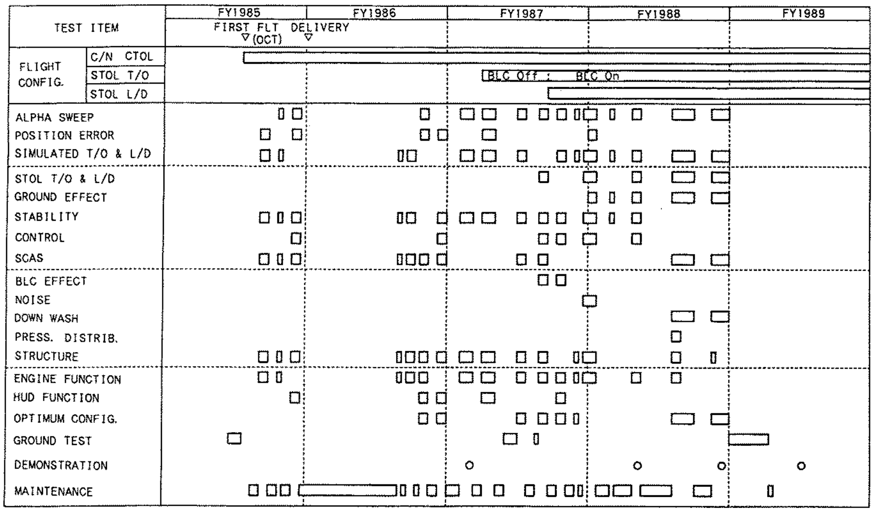

Figure 11. The Overview of the NAL QSTOL Flight Tests

Position error

The ASUKA has the usual standard pitot system with angle of attack vane and sideslip vane at nose boom.

Airspeed, The position error of the static pressure was derived from the fly by tower method linked with the tracking radar. Figure 12 presents the data obtained, it shows almost linear and 4% of speed error independent from the configuration. The Indicated AirSpeed of the cockpit is provided the corrected value by the DADC (Digital Air Data Computer).

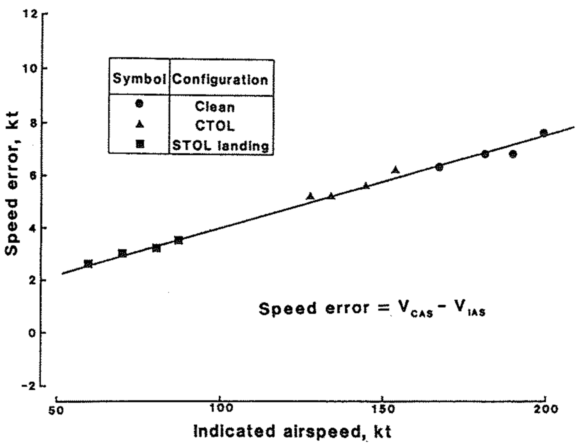

Figure 12. Position Error, Airspeed Calibration,

Angle of attack, The angle of attack vane is used for the artificial stall warning sensor, the data analysis and the pilot information at the cockpit instrument. Figure 13(a) shows the data obtained true angle versus vane angle with STOL L/D configuration. True angle of attack was calculated from airplane pitch attitude and flight path angle. It shows true angle is 0.83 times less than the vane angle. And there are no difference between the power setting and little change with the flap angle.

Sideslip angle, sideslip angle is used only for the pilot information at the cockpit instrument and data analysis.The true sideslip angle is calculated from the aircraft heading and ground tracking data from Inertial Reference Unit and the true airspeed of the standard pitot with the

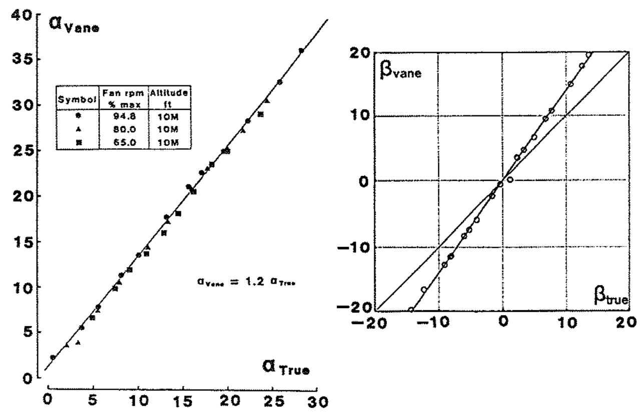

Figure 13. Position Error; Angle of Flow

assumption of the constant wind at the time. Figure 13(b) presents the result, it shows true angle is 0.74 times less than the vane angle on the average with flap angles.

Alpha sweep (static longitudinal) test

The static longitudinal characteristics is an important problem for the ASUKA project, numerous times of alpha sweep tests were executed. The "alpha sweep" test is a combined test of a static stability test and a stall test with wider range of angle of attack change,which increase angle of attack with quasi-steady condition. This "alpha sweep" test can replace several similar flight tests, such as static longitudinal tests, static stability tests, flight path stability tests, and stall tests.

To investigate the flow condition on the aircraft, tufts observation were used from the chaser and video camera at top of the vertical tail. The tufts can be monitored at the engineer seat in the fuselage in real time on a TV , and it was useful. A helicopter was mainly used for the chaser. Figure 14 shows the example of the tuft condition on the wing.

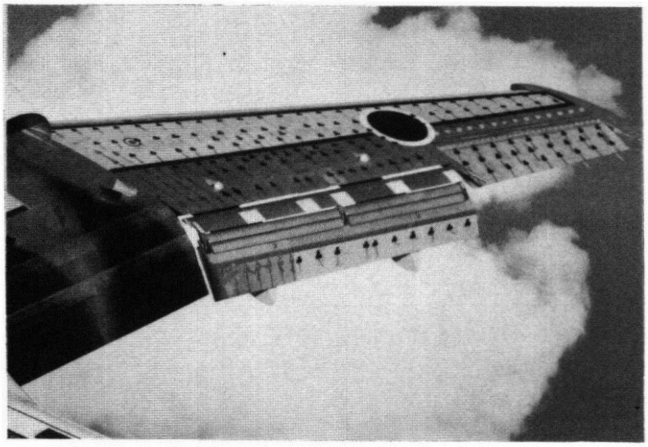

Figure 14. Tufts on the Wing

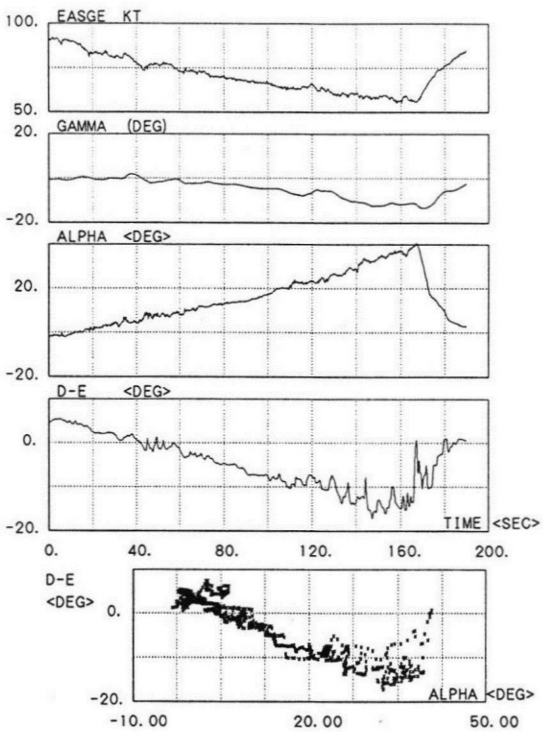

Figure 15. Time History of Alpha Sweep Test

The aerodynamic characteristics of a powered lift aircraft is strongly affected by power levels, so that it need to repeat several times with different power levels at the same configuration. Above that, as the engine power is also decrease with altitudes, it makes more complicated problem to get the whole ranges of aerodynamic characteristics. On the point of safety, we set the lower limit for the alpha sweep as 5,000 ft.

Figure 15 presents the typical time history of the alpha sweep test at configuration of STOL L/D (flap angle of USB/OBF= 60/65 deg.). Figure 15 shows elevator angle versus angle of attack simultaneously, the gradient of elevator indicates the tendency of static instability with angle of attack at extremely high angle of attack. However the change is quite mild, and the pilot can recover very easily without any conscious nose down control. Figure 16 presents the example of the result obtained from the same alpha sweep data. It shows a wing body data (without tail), which is derived from sub

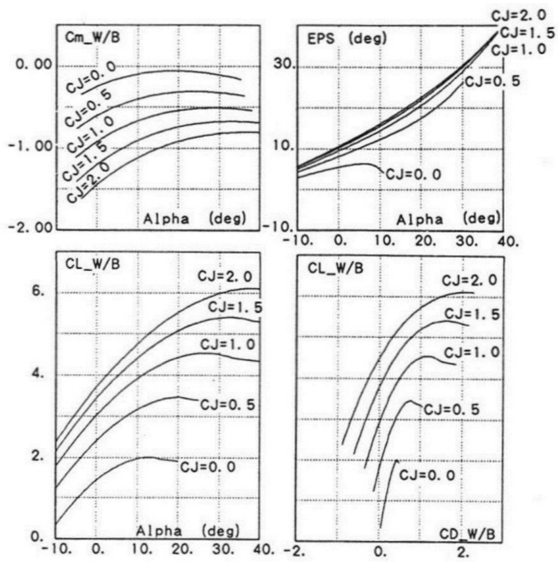

Figure 16. Longitudinal Characteristics; STOL L/D

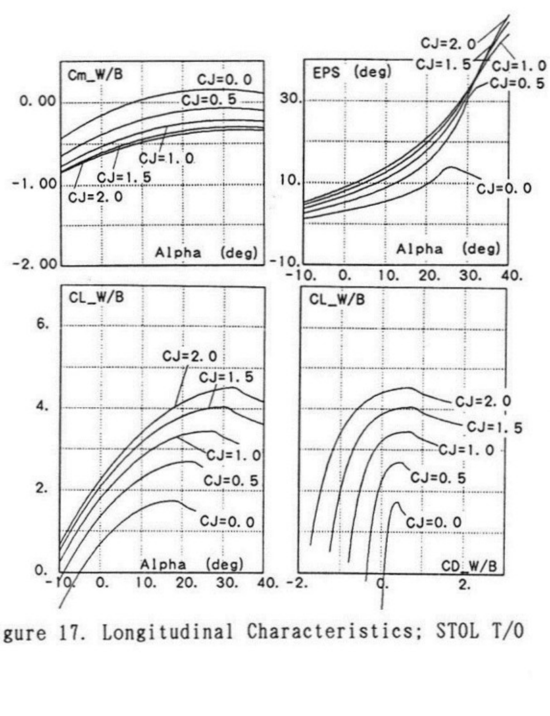

Figure 17. Longitudinal Characteristics; STOL T/O

traction of a tail component from total force or moment. The tail component can be obtained from the tail load or local flow measurement. Figure 17 presents the longitudinal characteristics of the STOL T/O (USB/OBF=20/30 deg.) configuration.

Another important diagram for STOL aircraft is so called V-Gamma diagram (airspeed versus flight path angle with power) shown in Figure 18. It shows the steady flight performance, and also suggests the control technique during approach. It shows that the powered lift STOL aircraft has naturally the decoupling V-Gamma characteristics, that is, with a constant pitch attitude flight path angles can be control only by the engine power.

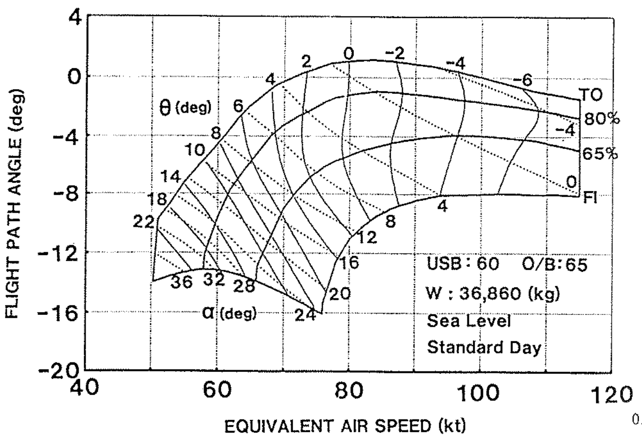

Figure 18. V-Gamma Characteristics

Ground effect

The limited length of the landing field requires more strict and repeatable touch down ability. For landing at the aiming point, it is important to examine the ground effect quantitatively for a powered lift aircraft. The method to measure the ground effect employed for ASUKA is "steady shallow flight path approach method", that is, at first establish the steady flight path with precise trim at about 300 to 500fpm of descent rate above the altitude at least twice of the wing span. After established the approach trim, keep the same attitude with only column control, without throttle, until touch down. The problem for the analysis is disturbance such as turbulent, gust, and control surface movement. The typical time history for the ground effect measurement is shown in Figure 19, and the result of the analysis is presented in Figure 20.

The ground effect on the downwash at the horizontal tail can be found from the flow measurement by the vane. Figure 20 shows that the ground·effect is appeared below the height of 0.4 times of the wing span, the lift is increased about 10% of the lift in free air, the drag is decreased, the downwash angle is also decreased.

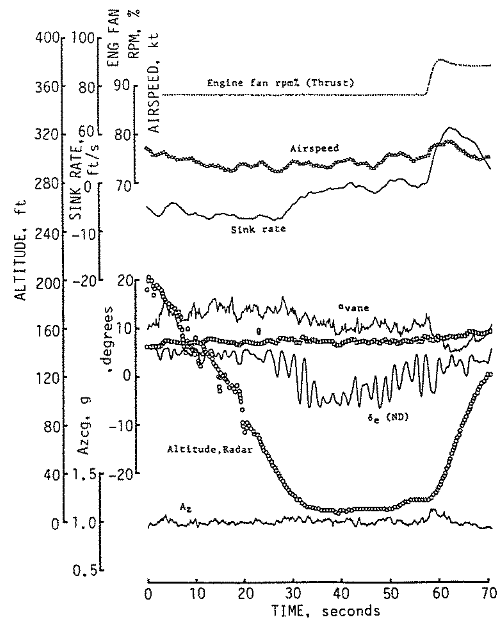

Figure 19. The Time History for the Ground Effect

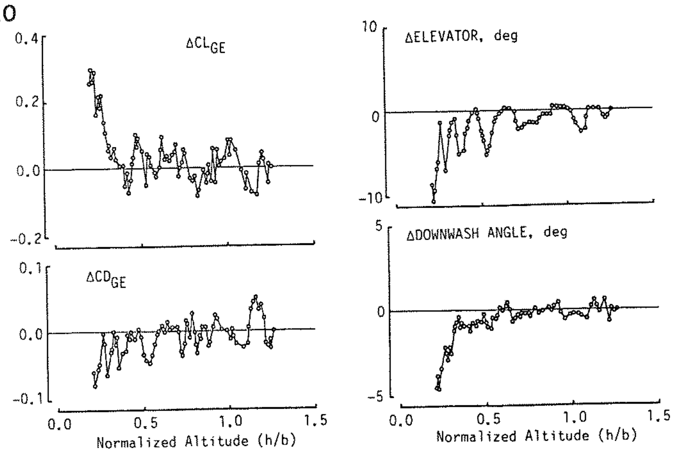

Figure 20. The Ground Effect

This decrement of the downwash angle generates large nose down moment change at the touch down. The positive lift increments make it difficult to land at a pin point. Consequently it is needed to clear the optimum way to flare.

Control technique for approach and landing

There are two problems for STOL approach and landing, one is to control the flight path, and another is to flare for touch down.

<u>Flight path control technique.</u> The power required curve at the airspeed range of approach and landing for powered lift STOL aircraft shows the very strong back-side characteristics. It requires the different flight path and airspeed control techniques from a conventional aircraft. As described before, the STOL control-technique is employed for ASUKA, the SCAS control law becomes very simple, and only two almost independent loops are required. But, it requires the pilot should be accustomed to this different control technique from CTOL. These two SCAS loops are the Pitch Attitude Control Wheel Steering loop, and the Flight Path Control (FPC) loop, as shown in Figure 21.

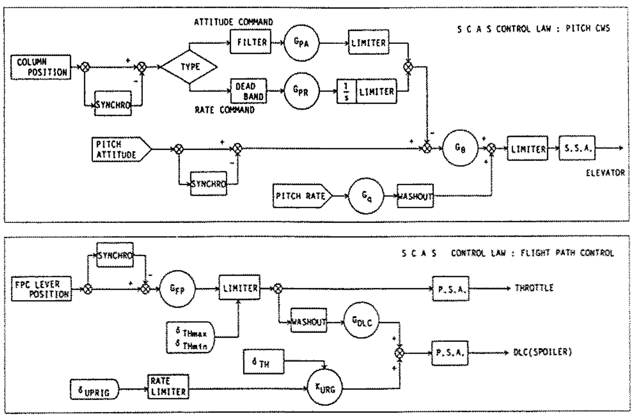

Figure 21. The SCAS Control Law, Pitch CWS mode and Flight Path Control Mode

<u>Flight Path Control mode.</u> This mode was originally designed that flight path change was mainly obtained from the power change, and the DLC, spoilers, compensated only the slow response of engines. But it became clear through the flight test that the pilots want to control with quicker response for the trivial flight path deviations. Then the design has changed that the DLC controls the flight path, and the engine power is used to get the long term changes of the flight path. Figure 22 presents the flight path response with the FPC. It works well and was evaluated sufficient to control the flight path, but still sluggish by the pilots.

Even the original FPC loop was designed to satisfy the flight path changes of more than +/- 2 degrees in 3 seconds for the greater input of the 2 degrees of path changes, but the smaller and quicker flight path control capability is also required by the pilots.

<u>Flare control.</u> The landing gear is designed for the limit descent velocity of 10 ft./sec on the basis of the FAR part 25, the regulation for transport category airplane. As the descent velocity of ASUKA is 12.7 ft./sec at the scheduled flight path, -6 degrees, at 72 kts, it need to flare from 12.7 to less than 10 ft./sec for touch down while keeping the precise touch down point.

Figure 23 shows the time history of the approach and landing, it shows two kinds of flare. Figure 23(a) is using

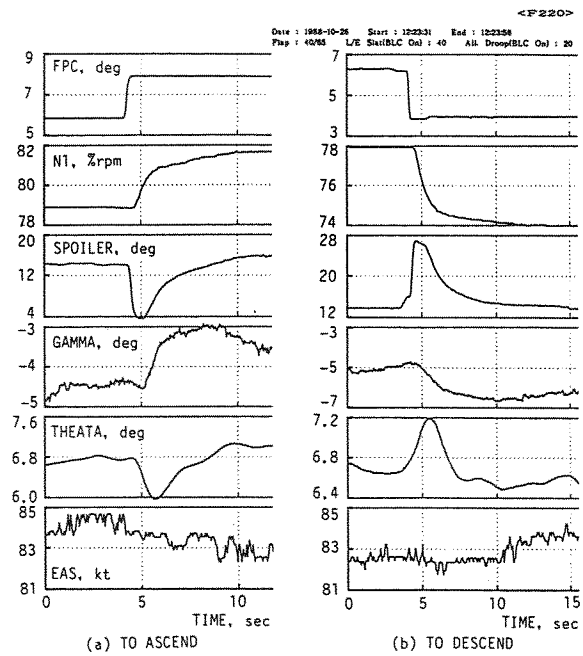

Figure 22. Flight Path Response in Flight

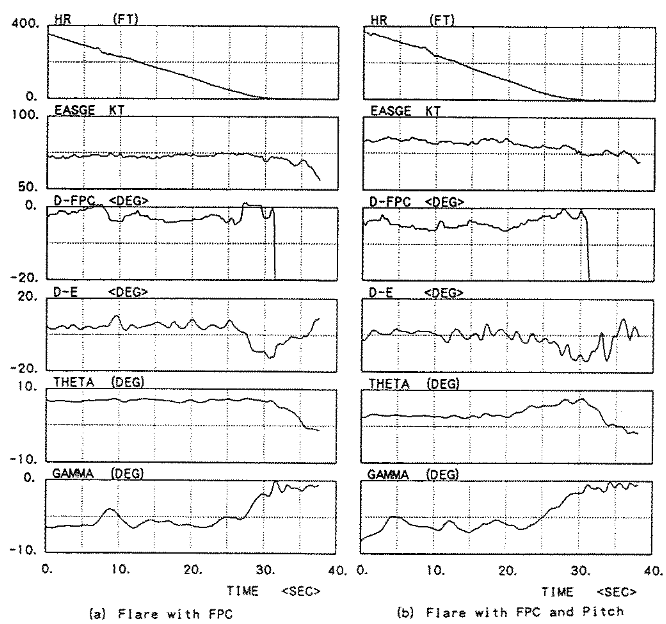

Figure 23. Typical STOL Approach and Landing

only FPC with keeping the pitch attitude constant, and Figure 23(b) uses both FPC and slightly nose up for touch down. Although this nose up motion induces decrement of the airspeed, the adverse descent velocity increment does not occur. As flare motion is carried out in a short time, either FPC or nose up can be used for the flare.

<u>Noise measurement</u>

The USB type powered lift STOL aircraft is considered to have a merit on the noise, due to noise shielding by engine installation on the wing, together with steeper climb out and descent operation. In addition, engine nacelles can be designed to attenuate engine noise by adding the tuned acoustic linings inside the inlets and fan ducts.

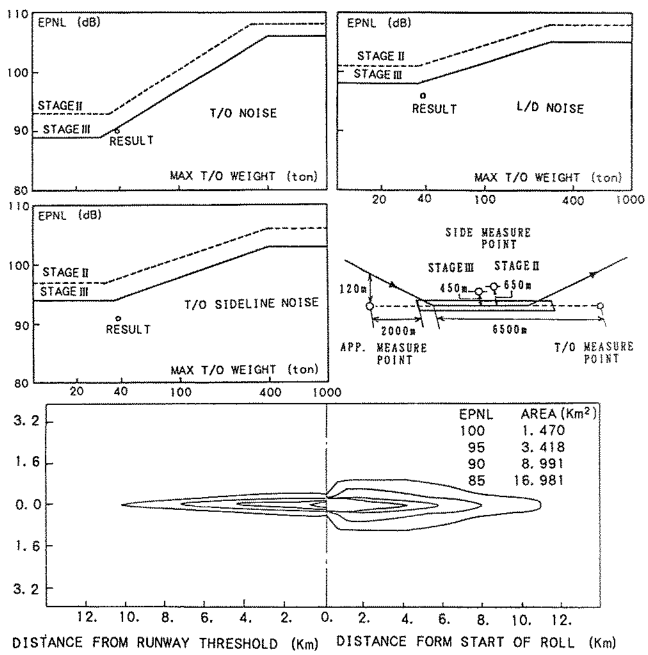

Figure 24. Noise Level of ASUKA

Noise measurement was conducted at Gifu air field basically according to the ICAO measurement procedure. There are three measuring points; 6.5 km ahead of and 0.45 km sideline from the takeoff brake release point, and 2.0 km backward the runway threshold for landing.

Measured noise levels are presented in EPNL (Effective Perceived Noise Level), and evaluated with the criteria by engine number and maximum takeoff weight.

The noise contour is drawn from the measured data by the computer processing. Figure 24 presents the measuring noise level and noise contour for STOL landing. The noise level of ASUKA is satisfied ICAO standard.

<u>Design criteria for STOL aircraft</u>

ASUKA was designed to evaluate and establish the design criteria for a powered lift STOL aircraft. Our problems in the design and flight phase are the subjects to be investigated for the design criteria and/or standard.

Some of them are as follows;

- stall airspeed,
- approach and landing airspeed,
- configuration change at go around
- stall warning,

It need to re-define the stall airspeed for a powered lift aircraft, because it is much varied with power levels. The minimum airspeed, "Vmin", is newly defined for ASUKA, which is depend on the power levels and engine operating conditions.

The approach and landing airspeed should have enough safety or maneuver margin. It is not enough for a STOL aircraft to set the airspeed multiplied by a constant factor like a CTOL. The angle of attack margin is also necessary for STOL. At the design phase of ASUKA, margins were set as the airspeed of 20 kts to the minimum airspeed at maximum power, and the vertical gust of 15 kts for angle of attack.

It is sometimes difficult to have enough climb performance with final landing configuration for STOL. The configuration change for go-around can give a good solution for safety. Then, the go-around switch is provided with ASUKA on top of the primary control lever (FPC lever), it allows a pilot to change the flap angle with just a finger action.

The operating point of the artificial stall warning should be determined appropriately. We tentatively set the point below 90% of the angle between maximum angle of attack and zero lift angle of attack, following the military specification of MIL-F-8785B.

The big problem for a powered lift aircraft is difficulty to prove in-flight condition on the marginal condition, due to large power effect.

As described above, there are some items to be examined of the design criteria for a powered lift STOL aircraft, for example;

- definition of the minimum airspeed,
- verification method for minimum

airspeed,

- appropriate required safety margin, of airspeed, angle of attack and maneuver,
- appropriate required longitudinal and lateral directional controllability.

The guest evaluation pilot program

The NASA Ames Research Center in the United States is also conducting the research on the USB type STOL aircraft from 1974. The agreement of the "NAL/ NASA ASUKA/QSRA Pilot and Technical Information Interchange Program" was officially concluded between Japan and the United States in 1985.

During this co-operative research, ASUKA was evaluated by the NASA research pilots. And they gave us many advice and comments. Some of the comments are as follows;

- ASUKA has good longitudinal and lateral directional stability in every configuration, especially in the landing configuration even without the SCAS,
- the response by the Flight Path Control mode of the SCAS is still just sluggish, but controllable for the approach and landing,
- there is no problem to perform the landing with simulated one engine failure,
- Head-Up-Display is useful to aim the precise touch down point,
- the attitude hold of the pitch and roll CWS is sufficient, except rate command type pitch CWS,
- the Engine Failure Compensation mode of the SCAS is very effective.

Concluding remarks

As described above, we have executed Powered Lift Technology Research Project for about 13 years (from 1977), and completed the flight test in 1989. To build the airplane for purely technological research, the design and development were performed in the orthodox way, that is, various basic tests were executed to obtain the technical data.

Many fruitful accomplishments were obtained through the flight test and the design and development of the ASUKA.

In spite of the aerodynamically unrefined form, the basic concept of the USB was proved, and the control technique to fly at very low speed range was verified.

Because the wing area can be reduced by the powered lift technology, the cruising efficiency can be improved significantly. The research and development on the powered lift technology will be the key for the future aircraft.

We consider the ASUKA project will be successfully completed by 1992, and the important work to be left for us by that time is to examine and establish the design criteria and/or standard for a powered lift STOL aircraft.

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Everybody won't forget these long and short happy times in the ASUKA project.

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