DESIGN AND FLIGHT TEST ON HIGH AOA/SPIN CHARACTERISTICS OF XT-4 INTERMEDIATE JET TRAINER

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Abstract

This paper describes the designs, development tests, and flight tests on high AOA/spin characteristics of XT-4. Because of the requirement for spin training, a lot of attention was paid to the design of its high incidence characteristics. Rotary balance WTT, spinning WTT and even spin test using RPV models were conducted to predict the post-stall behavior of the XT-4.

The flight test aircraft was equipped with special emergency hydraulic system and spin parachute, etc. The tests progressed step by step, evaluating the stall characteristics, response of control misapplications, spin, and recovery from spin based on MIL-F-8785C, MIL-S-83691A guidelines. It was found that the XT-4 is extremely resistant to departure during the maneuver and also has the capability to get into the intentional spin followed by a hands-off smooth recovery from any mode with engine distortion tolerance.

While the spin characteristics were satisfactory, the full scale aerodynamics were slightly different from the predictions. "Simulation matching" revealed that it was mainly due to the overcorrection from the wind tunnel models to the full scale airplane.

Nomenclature

AOA, α	Angle Of Attack
ATF	Altitude Test Facility
$Cn\beta$ dyn	Directional Departure Parameter $Cn\beta\ dyn = Cn\beta \cdot \cos\alpha - (Iz/Ix) \cdot C\ell\beta \cdot \sin\alpha$
LCDP	Lateral Control Departure Parameter $LCDP = Cn\beta - (Cn\delta a / C\ell\delta a) \cdot C\ell\beta$
PSG	Post-Stall Gyration
RPV	Remotely Piloted Vehicle
WTT	Wind Tunnel Test
β	Angle Of Sideslip

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1. Introduction

The Technical Research and Development Institute (TRDI) of the Japan Defense Agency initiated the development of the XT-4 intermediate trainer in October 1981. The first flight was made in July 1985 and the developmental flight tests were completed in March 1988. The initial production airplane was delivered to the Japan Air Self-Defense Force (JASDF) in September 1988.

The aircraft was designed and manufactured by the prime contractor Kawasaki Heavy Industries Co., Ltd. and two other manufacturers under initiative of TRDI. Since the spin training had been required, aerodynamic designs at high incidence were considered carefully.

The aim of this paper is to present the process of design and development testing and to compare the differences between the predictions and the flight test results.

2. Aircraft description

The XT-4 is a twin engine tandem two seats prototype trainer for the JASDF. (Fig. 1) The airplane has good flight and handling characteristics in a wide envelope from low speed to the transonic region by adopting a new transonic wing. So, it enables the trainees to progress from beginner's class to advanced one easily.

Design performance

Take off weight	: about 5.5 ton
Engine static thrust	: about 1.7 ton ×2
Maximum speed	: over 500 kt
Stall speed	: about 90 kt
Climb limit	: over 40,000 ft
Range	: about 700 nm

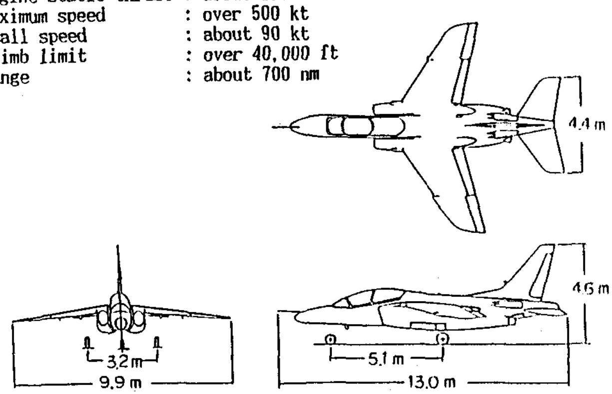

Fig. 1 XT-4 three views and design performance

The XT-4 is powered by two Ishikawajima-Harima XF3-30 turbofan engines. The engine had been developed in advance to the aircraft and was designed to have superior distortion tolerance even at high AOA/spin environment.

The primary flight controls of this aircraft are power operated by dual hydraulic system with artificial feel units. The pitch feel units consist of spring feel, hydraulic q-feel and bob-weights. The roll and yaw controls are spring feel only. In yaw control, a rudder limitter and yaw damper system are fitted.

As for new technologies, the following systems are adopted.

- Through the canopy type ejection system
- Attitude and heading reference system using ring laser gyro
- On-board oxygen generating system

3. Aerodynamic designs for stall/spin characteristics

The requirements for stall/spin characteristics of the XT-4 were as follows.

- Stall characteristics : distinct stall signs and easy recovery from stall
- Spin characteristics : spin training capability and easy recovery from spin

Considering these requirements, the configuration of the aircraft was developed as follows.

Wing

Giving a suitable downward twist, a "dog-tooth" was adopted to suppress the pitch-up tendency at high incidence. A small fillet was fitted on the wing root leading edge in order to supplement the directional stability at high incidence.

Horizontal tail

The horizontal tail was arranged as low as possible to avoid pitch-up and maintain the control surface power at high incidence within a limitation of exhaust flow interaction.

Vertical tail

The vertical tail was given a considerable "look-up angle" from the wing to maintain the directional stability/rudder power at high incidence and also was installed ahead of the horizontal tail not to be immersed in the wake of the wing and horizontal tail.

Forebody

The forebody was shortened as much as possible and the nose was made round to suppress the asymmetric aerodynamic force at high incidence. A large radius was given at the bottom corner of the forebody to reduce the bad influence on the intake at large sideslip.

Intake/duct

The fairly round lip, near straightened duct and large contraction ratio were adopted to minimize the engine face distortion level at high incidence.

4. Development tests

Development tests during the design phase are described below in conjunction with the design subjects. (Table 1)

Investigation of static directional stability

The main subject assuring the high AOA characteristics is to prevent lateral/directinal departure, and it is necessary to maintain the directional stability up to as high incidence as possible. The configuration to keep the static stabilities was obtained from the low speed WTT and the high AOA WTT. The departure parameters, $Cn\beta$ dyn and LCDP, were used to evaluate it.

Investigation of aerodynamic force in motion

In order to predict the post-stall/spin characteristics, it is important to obtain the aerodynamic force in motion accurately. Wing static pressure distributions around the stall AOA were measured in the low speed WTT to estimate "damping in roll" (Clp). The aerodynamic forces in rotation were also obtained from the rotary balance WTT and used to investigate the steady solution of the spin mode.

Verification of dynamic response

RPV testing was very useful to identify the spinning motion. The RPV spin test was carried out using 20% scale free flight models. Test results were used to improve the prediction accuracy of the transient characteristics by "matching" in motion and correcting the aerodynamic derivatives. Spinning WTT was also carried out to determine what steady mode can exist and how to recover from it.

Aircraft - engine compatibility

Intake performance was evaluated in the low speed intake WTT using the distortion index as a guideline. The engine functions were also examined in the engine ATF test where the inlet distortion level at spin was simulated by placing the distortion plate in front of the engine. To correlate the compatibility of the airplane motion, intake performance and the engine characteristics, the allowable $\alpha \sim \beta$ envelope was defined.

Flight simulator test

Several stages of the flight simulator tests were carried out applying the most credible aerodynamic data in each stage. In the earlier stage of the development, stall/post-stall characteristics were evaluated and reflected to the aircraft configuration. In the later stage, the spin mode and operating procedures were investigated, while the special equipments for the test aircraft, — spin parachute dimension, aerodynamic load on the chute, emergency hydraulic source capacity, etc. — were examined.

Prediction of the spin mode

Since the aircraft was intended to be used for spin training, it was important to confirm the spin mode, to establish entry/recovery procedures and to assure the engine functions. Concerning the critical mode, like "flat" in particular, the possibility of the mode and the recovery characteristics/procedures were also investigated.

Basic design stage. The extremely steep, slow spin mode was predicted from the balance of inertia/aerodynamic moments which were estimated based on the low speed WTT data analysis. The rotary balance WTT data indicated the same results.

Detailed design stage. The RPV spin test results showed the same mode, but the oscillation of motion was larger than the earlier prediction. "Simulation matching" indicated that damping in roll in the post-stall region was reversed (namely negative roll damping), but the full scale simulation using the corrected roll damping displayed the less oscillatory mode than the model. On the other hand, it was found that there could be a flat and inverted spin mode at this stage.

The spinning WTT results showed the presence of each mode, steep, flat and inverted, and the final full scale simulation indicated that there could be a flat and inverted spin mode other than steep. However, there was no mode other than steep in the full scale flight tests. These are summarized in Table 2.

5. Test aircraft

Flight tests on high AOA/spin characteristics were mainly assigned to the 4th prototype which was specially equipped with emergency hydraulic system and spin parachute, etc. (Fig. 2)

Spin parachute system

A spin parachute was equipped as the emergency recovery device. Parachute system consists of the chute deployment mortar and the chute release separation bolt. The power of both the deployment and release is provided by the pyrotechnic cartridge and the electric control of those as the independent dual system for reliability.

Table 1 Summary of development tests

	Test name [Model scale]	Data obtained	Relation to design , etc .
Static WTT	Low speed WTT [15%]	· 6 components of aerodynamic forces · Effectiveness of control surfaces · Static pressure distribution · Effects of aerodynamic devices	· Design of basic configuration · Investigation of aerodynamic devices · Basic aerodynamic data
	High AOA WTT [8%]	· 6 components of aerodynamic forces · Effectiveness of control surfaces	
Dynamic test	Rotary balance WTT [8%]	· 6 components of aerodynamic forces in rotation · Effectiveness of control surfaces · Effects of aerodynamic devices	· Prediction of steady spin mode solution · Prediction of aerodynamic force in motion
	RPV spin test [20%] (free flight model test)	· Basic response data · Effects of aerodynamic devices	· Prediction of the full scale airplane post-stall characteristics
	Spinning WTT [3.5%]	· Spin mode survey · Recovery characteristics · Effects of aerodynamic devices · Spin parachute effects	· Prediction of spin modes · Investigation of recovery procedures · Selection of spin parachute
Aircraft-engine compatibility	Low speed intake WTT [16.7% forward fuselage]	· Intake basic characteristics (Total pressure recovery/distortion)	· Intake/duct design
	Distortion plate WTT	· Characteristics of distortion plate	· Verification of distortion plate
	Aircraft-engine compatibility test (ATF test)	· Engine functions in simulated altitude	· Verification of intake
Pilot evaluation	Flight simulator test	· Pilots comments on stall/post-stall/ spin characteristics · Entry/recovery procedures · Special equipment data of the test aircraft	· Design of aerodynamic configuration and control limitters · Establishment of operational procedure · Flight test procedures · Design of special equipment of the test aircraft

Emergency hydlaulic system

This system would be effective in case of both engines flame-out during spin testing and consists of electrical pump, battery and accumulator, etc.

Additional cockpit instrumentation

The following additional instruments were fitted in the cockpit. (Fig. 3)

- AOA gauge(±90°)
- Sideslip gauge (±40°)
- Single pointer altimeter
- Visible and audio low altitude warnings
- Direction of yaw lights
- Spin parachute control panel, main/sub
- Spin parachute deploy button on the stick

Rudder pedal limitter cable device

To limit rudder deflection in the spin test, rudder pedal stroke can be limited by this device in the cockpit. The limit angle is adjustable by replacing a limitter cable. The pedal limitation can also be released in flight by pulling up the release handle.

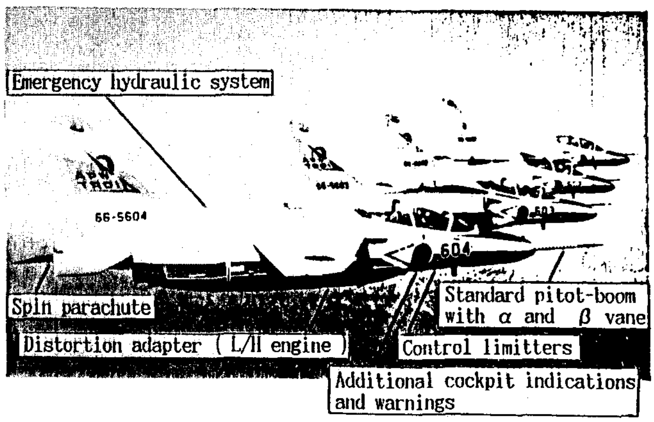

Fig. 2 XT-4 test aircrafts

Aileron - stabilator control limitter

Since some kinds of control misapplications after stall might cause the engine flame-out due to the excessive α or β, the aileron deflection near the stick full aft was limited and the neccesity was examined in the flight tests.

Distortion adapter / standard pitot-boom

Pitot rakes for measurement of intake distortion level were fitted in front of the left engine. The test aircraft was equipped with a standard pitot-boom with α and β vane.

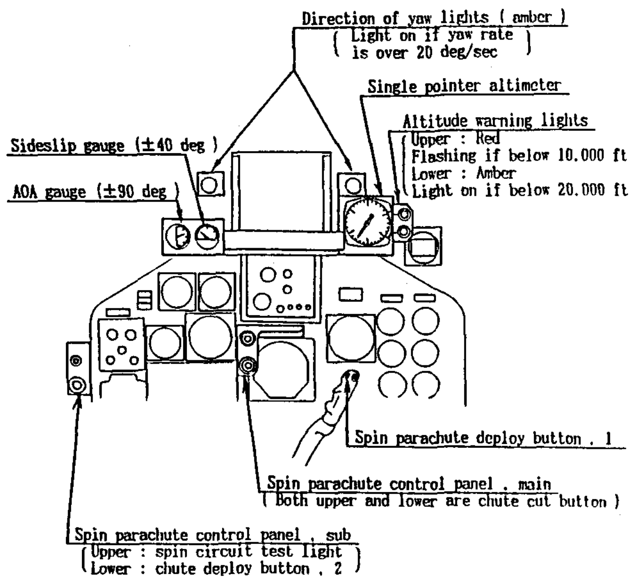

Fig. 3 Additional cockpit instrumentation

Table. 2 Summary of spin mode existence

Spin mode	Prediction of basic design stage	RPV spin test results	Spinning WTT results	Final prediction	Flight test results
FLAT ·Fast rate ·$\alpha \geqq 60$deg	Not exist	Not exist	Exist	Possibly exist	Not exist
STEEP ·Slow rate ·$\alpha \geqq 30$deg	Exist	Exist (oscillatory)	Exist	Probably exist (mildly oscillatory)	Exist (but heavily oscillatory at stick full aft)
INVERTED ·$\alpha \leqq -30$deg	Not exist	Not exist	Exist	Possibly exist	Not exist

6. Flight test

Test schedule

101 sorties out of a total of 616 XT-4 flights were assigned for the stall/spin tests. 987 stall/spin trials were conducted step by step in the developmental flight tests. (Fig. 4)

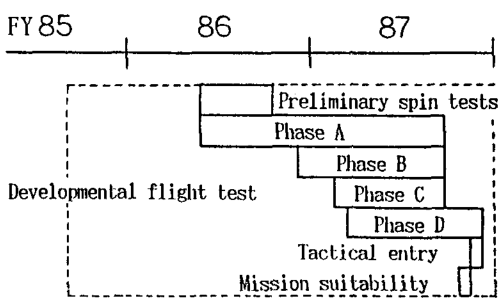

Fig. 4 Spin test schedule

Preliminary spin tests were planned to confirm the functions of the special equipments, and to get the aircraft baseline stability and the antenna pattern of the instrumentation telemeter. Then phase A ~ D and tactical entry tests were conducted, based on MIL-S-83691A which defines the procedures for verification of the stall/spin characteristics.

- Phase A : stall approach
- Phase B : momentary control misapplications after stall
- Phase C : control misappliations for 3 seconds after stall
- Phase D : control misapplications for 15 seconds or 3 spin turns.
- Tactical entry : control mishandling anticipated in the tactical/aerobatic maneuvers

Spin training procedures for practical use were evaluated in the mission suitability test.

Preparation for stall/spin tests

In consideration of the critical situations in the stall/spin tests, a special monitoring team, which consisted of a test director, a ground pilot and engineers, was organized and trained. The telemetered parameters were monitored, using not only the conventional pen recorders, but also the graphic displays for the airplane attitude and the simulated head-up display. X-Y plotter was also used for $\alpha \sim \beta$ locus monitoring. The flight test area was selected to allow the ground real-time monitoring. (Fig.5) A two seat F-15 aircraft was assigned as the chaser.

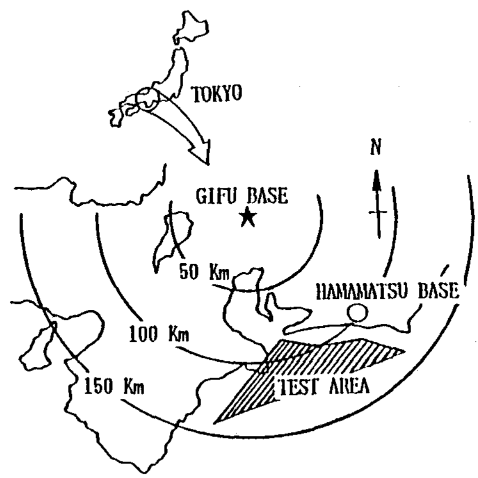

Fig. 5 Flight test area

Table. 3 Prepared Recovery procedures

Procedure No.	Recovery controls			Notes
	Stabilator	Aileron	Rudder	
1	Neutral	Neutral	Neutral	Hands off, for all modes other than flat
2	Full aft	Neutral	Full anti-spin	For flat mode
3	Rudder pedal limitter release*			* Maximum rudder deflection 30 deg
4	Full aft	Neutral	Full anti-spin	
5	Full aft	Full in-spin	Full anti-spin	in-spin : in the direction of spin
6	Neutral	Neutral	Full anti-spin	
7	Full aft	Neutral	Neutral	
8	Hands off and spin parachute deploy			If altitude below 20,000 ft
9	Bail out			If altitude below 10,000 ft

Flight test method

Basically flight test was planned according to MIL-S-83691A procedures. The entry altitude was selected at 20,000ft in phase A, 35,000ft in phase B~D respectively. In the spin testing (phase D), the controls were misapplied at the prescribed AOA including the 4 kinds of misapplications which consist of aileron or rudder alone and combinations of these (cross or with). After 3 spin turns or 20 seconds, the recovery controls were to be applied. Prior to the phase D flight testing, the recovery procedures were established for safety. (Table 3)

7. Flight test results

Stall characteristics (cruise configuration)

Approaching to 1G-stall, wing rock started just below the stall AOA, but pilots could continue to pull the stick until full aft while correcting the motion. At accelerated stall (high speed), increasing AOA caused strong buffet and finally reached heavy buffet with light wing rock. While stall warning at high speed was given by buffet, stall warning at low speed was supplemented by an artificial aural tone because of the lack of the natural warning. (Fig.6) It was quite easy to recover from stall by hands-off only.

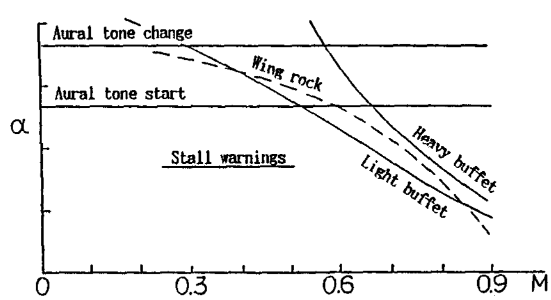

Fig. 6 Stall warnings

Improvement of stall characteristics (landing configuration)

In the earlier stall tests of the landing configuration, wing drop had occured at stall AOA and could not be supported by aileron. To solve this problem, the flow pattern of the wing upper surface was investigated by "tufts" observation. It was found that the flow separation started from just inside of the "dog-tooth" and progressed inboard so rapidly that the unbalance of separation on both wings caused sharp wingdrop. Then, several aerodynamic devices were tested to improve the wing drop. (Fig.7) In the flight tests, a "dog-tooth plug" showed best improvement and it made the motion at stall mild, so it was adopted to the production airplane.

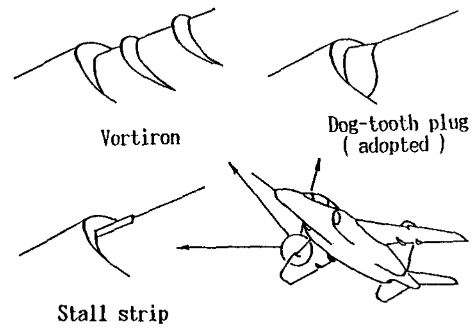

Fig. 7 Aerodynamic devices tried to improve stall characteristics of landing configuration

Departure characteristics (phase B,C)

Rudder/aileron misapplications up to 3 seconds in the post-stall region showed the normal control responses and showed no departure tendency. But the aileron input near the stick full aft caused adverse roll, which is a typical high incidence phenomenon induced by the aileron adverse yaw. This phenomenon was not interpreted as a departure,because pilots could recover immediately and did not result in PSG or spin.

Spin test (phase D)

Flight tests showed that the XT-4 has two kinds of spin modes. (Fig.8) One is the steep, slow, oscillatory mode which is characterized by heavy rolling oscillation. Any combination of aileron and rudder input at the stick full aft results in this mode. The other is the extremely steep, slow, smooth mode which is obtained by rudder input at about 19 degrees of AOA. The recovery from any mode can be made immediately by hands-off only. With the two modes above, spin training patterns were established. The flat and inverted mode which were anticipated at the final prediction stage did not appear.

Tactical entry

The following trials were made as the tactical entry.

- Inverted stall approach and control mishandling at inverted stall. (stick full forward)
- Control mishandling during dive recovery
- Control mishandling at the top of a loop
- Recovery from vertical attitude and effect of recovery lag
- Tail slide (Fig.9)

It was found that the airplane recoverd safely from any of these cases without departure.

From all of the results above, the departure/spin tendency of the XT-4 were classified to be "extremely resistant", and it was concluded the aileron-stabilator limitter could be removed.

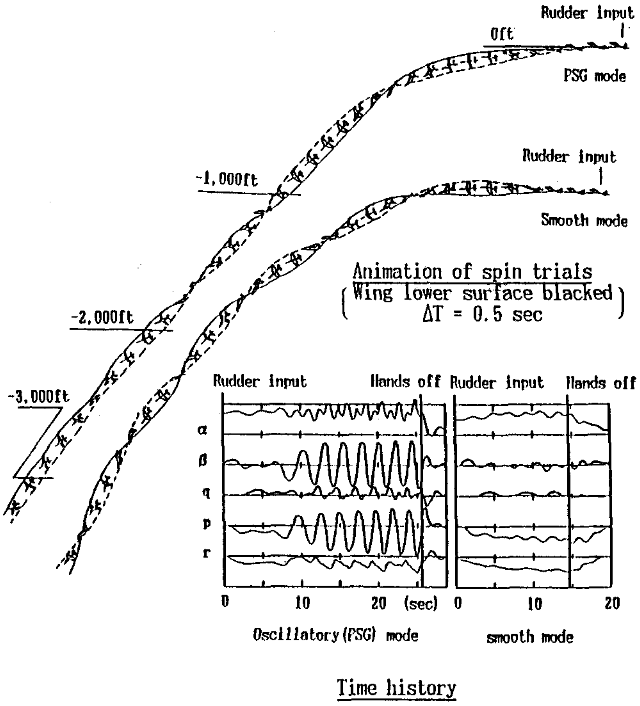

Fig. 8 Spin modes for training use

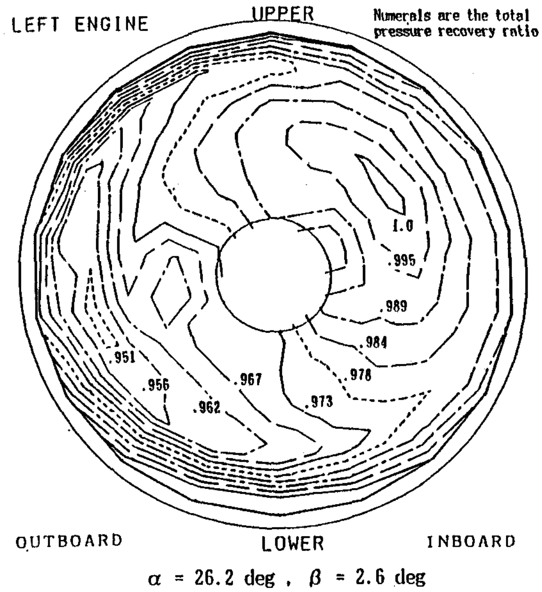

Fig. 10 Total pressure distribution in front of the left engine at post-stall region (phase D trial)

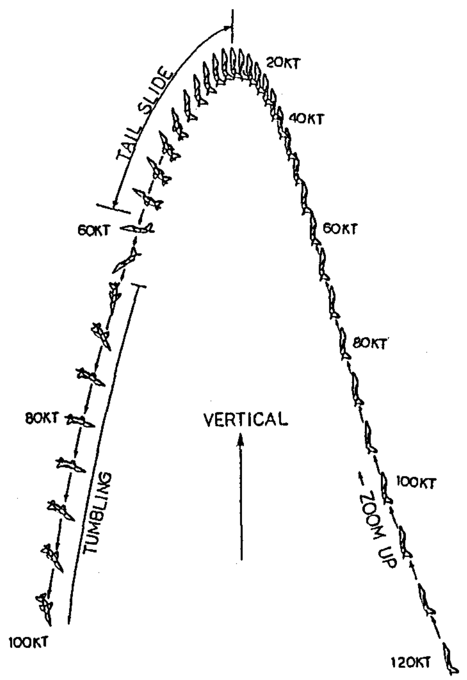

Fig. 9 Tail slide behavior

Engine characteristics

The engine functioned quite stably at high incidence and there was no tendency to stall or surge during spin with any setting of power from idle to military and even with quick snap of the throttle. An example of intake distortion measurement is shown in Fig.10.

8. Matching of the aerodynamic derivatives

Predicted aerodynamic derivatives were matched with the flight test data phase by phase, and step-up simulation tests were conducted by the corrected aerodynamic derivatives in order to predict the next flight test results.

Lateral/directional stabilities and the effectiveness of control surfaces were reviewed from the results of phase B or C. It was found that the full scale post-stall separation phenomenon occured earlier than the predictions by 2 degrees of AOA. This can be explained by the too much extension(4 degrees of AOA) during the corrections from the WTT data to the full scale airplane. (Fig.11)

Since the earlier trials of phase D showed the heavily oscillatory mode compaired with the prediction, "matching" of the phase D was concentrated to search for the derivatives which are related to the oscillation. It was found that the excessive oscillation was due to the roll damping which fell into the more unstable side than the prediction. (Fig. 11,12) Again, this was caused by the overcorrections from the WTT/RPV model to the full scale airplane.

In general, the aerodynamic derivatives of the full scale airplane verified by "matching" were not so far from these of the models. The main cause of the defference between the flight and predicted spin mode was the amount of corrections applied to the WTT data.

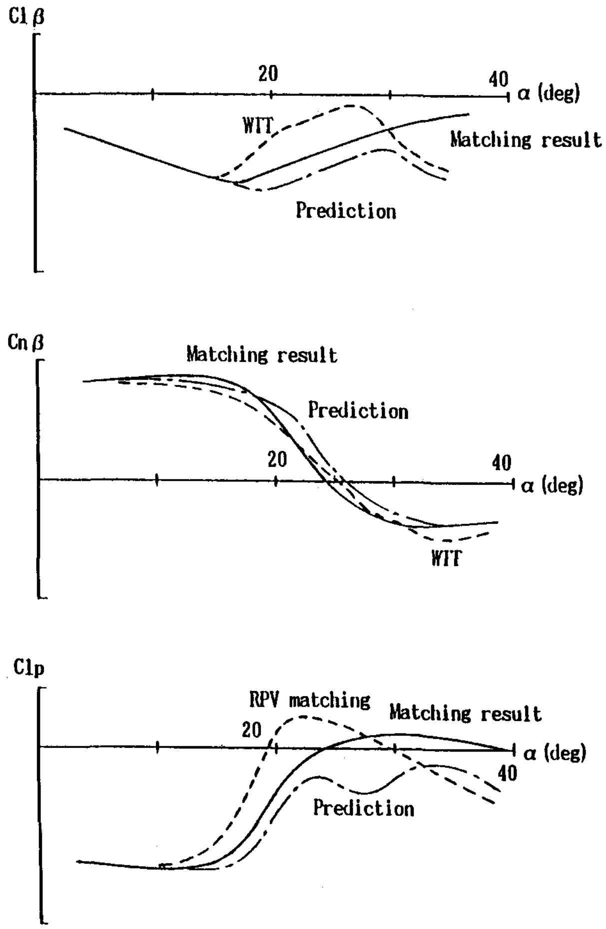

Fig. 11 Matching results, Clβ, Cnβ and Clp

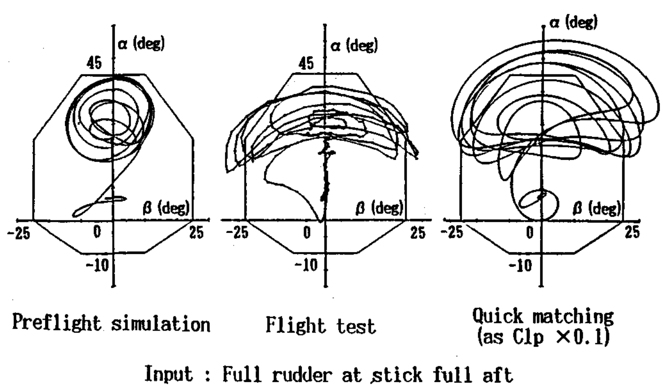

Fig. 12 Example of quick matching result of phase D

9. Concluding remarks

The XT-4 resulted in an excellent trainer specially in high AOA characteristics. The design aim was to not departure and to maintain control up to as high AOA as possible without relying on the complex system. During the development, we utilized as many design tools as possible to verify the prediction.

Although the full scale airplane characteristics did not exactly coincide with the predictions, the full scale aerodynamics were not so much different from that of the 15% WTT model or the 20% RPV model.

"Matching" of the aerodynamics and step-up simulations were mandatory to make the spin tests progress safely and efficiently. The simulator was very effective to survey and find out the entry procedure, from which intended data were derived, throughout the spin testing.

The engine functioned quite stably at high incidence and there was no tendency to stall or surge during the spin. It gave us very safe feelings during the spin tests.

It is believed that the deployment of the T-4 will contribute to the effective training for the highly maneuverable fighters of the coming decades.