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Development Research and Crucial Technology Analysis of Scaled 3-Bearing Swivel Duct Nozzle Rotary Drive System

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Abstract. The 3-bearing swivel duct (3BSD) nozzle for short-range/vertical take-off and landing(S/VTOL) fighters is a crucial component for aircraft to achieve vertical and/or short take-off and landing, which significantly improves the manoeuvre ability of the aircraft, while the nozzle rotary drive system is the crucial technology for S/VTOL functions which has significant impact on the fighter performance. Based on the principle and characteristics of the 3BSD nozzle, this paper systematically reviews the development and evolution of the 3-bearing swivel duct nozzle, and analyses and summarizes the types and characteristics of the 3BSD nozzle rotary drive system. Three crucial technologies of the 3BSD nozzle rotary drive system are evaluated and discussed in detail. Suggestions on future research and development of equipment are given.

1 Introduction

S/VTOL aircraft combines the advantages of fixed-wing aircraft and rotary-wing aircraft. It can significantly improve the aircraft's the take-off and landing ability to reduce the requirements for the take-off and landing environment, the higher flight speed can improve manoeuvre ability as well. From theory to practice, it has gone through more than 70 years of development. At present, the main types of its power plant are: lift engine, thrust vector nozzle engine, lift fan system, spiral rotor system, and stallable or retractable rotor system [1-6].

The thrust vector direction of the thrust vector nozzle engine can be changed by rotating the nozzle angle. The steering mechanism of this engine exhaust nozzle is represented by the British Harrier fighter, the Yak series of Russia, and the F-35B fighter of the United States. According to the current practice [7,8], in terms of lightweight, high efficiency, stealth performance and control technology, the 3BSD nozzle can meet the requirement of S/VTOL propulsion system.

S/VTOL aircraft using thrust vectoring not only has a conventional aerodynamic rudder surface, but also uses large angle thrust vector and various forms of lift devices to provide direct lift. In order to meet the different thrust direction requirements, the S/VTOL aircraft needs to be deflected by more than 90°. The nozzle end rotation stroke reaches 180°, and the 3BSD nozzle rotation angle has a strong nonlinear relationship with the thrust vector rotation angle. Therefore, the 3BSD nozzle rotary drive system is considered as a crucial technology that directly affects S/VTOL aircraft performance.

The main purpose of this paper is to review the characteristics and development of the 3BSD nozzle rotary drive system basing on its basic principle and characteristics. The layout of this study is organized as follows: Section 2 is aimed at explaining the principle and characteristics of the 3BSD nozzle, and then, the research status of it is presented in Section 3. In Section 4, various of key technologies of each type of 3BSD nozzle presented in the former section are discussed. At the end of the Section 4, these types of BSD nozzle are compared on basis of their beneficial characteristics as well as their drawbacks. In the last section, the future development on 3BSD nozzle is discussed.

2 Principle and Characteristics of Scaled 3-Bearing Swivel Duct Nozzle

2.1 Structure

The 3BSD nozzle is mainly composed of three nozzle ducts and rotary drive system, between nozzle ducts are connected by a thin-walled ring bearing. The end section of the first duct inlet is circular, the inlet of 3BSD nozzle first duct is fixed with the outlet of the engine, the end face of the outlet is circular too, and the diameter is the same as the diameter of the inlet end section of the second duct. The second duct is an elliptical tube. Both the outlet end sections of the second duct are circular. Meanwhile, there is an angle between the elliptic axis and the normal of oblique section. The end section of the third duct is round, and the diameter of the outlet of the second section is the same.

In normal flight mode, the three-ducts keeps the centre line coincident and the thrust is behind the engine axis. In vector flight mode, the rotary drive device drives the nozzle to rotate, changing the nozzle orientation.

2.2 Law of movement

During the movement of the 3BSD nozzle, the three-duct nozzle is sustained in a certain fixed plane. the relationship between the rotation angle of each nozzle and the total vector angle is expressed as follows [1]:

$$\Omega_1 = -arctan(tan(\Omega_2/2)\cos\theta) + \delta_{Ny};\ \ \Omega_2 = arccos\left(\frac{\cos(\delta_N/2) - \cos^2\theta}{\sin^2\theta}\right);\ \ \Omega_3 = -\Omega_2.$$

where Ω_1, Ω_2 and Ω_3 denote the three angles input quantities of the 3BSD nozzle, δ_N and δ_{Ny} denote the longitudinal and lateral deflection angles of the nozzle, θ denotes the angle formed by the nozzle end section and the pipe cross section. When $\Omega_2 = \pi = -\Omega_3$ the maximum vector angle is reached： $\delta_N = 4\theta$ [1].

3 Overview of the Development of 3BSD Nozzle

3.1 Foreign typical 3BSD nozzle

In 1960, Jack [9] first proposed the concept of a rotating nozzle that mounted a gear on the outer wall of the nozzle and rotated it through the gear drive.

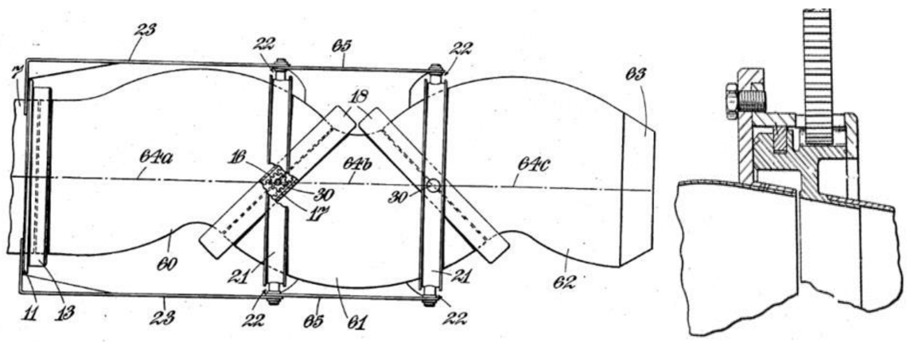


Figure. 1. Jack three-stage rotary nozzle structure

In 1966, the motor used in the multi-section wedge nozzle developed by Carroll [10] has two output shafts, which drive the gears to drive the synchronous rotation of the two bearings of the second and third duct.

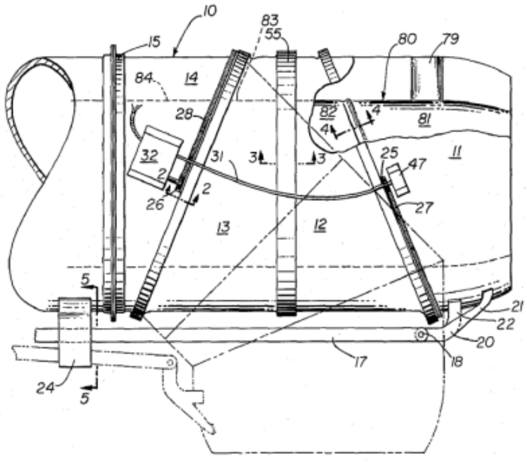


Figure. 2. Carroll multi-stage rotary nozzle structure

In 1969, the nozzle proposed by Gerhard [11] was composed of four straight sections with irregular curved surfaces. The nozzles of each section were connected by bearings. Each section of the nozzle was equipped with gears to ensure the synchronous deflection of each upper and lower section.

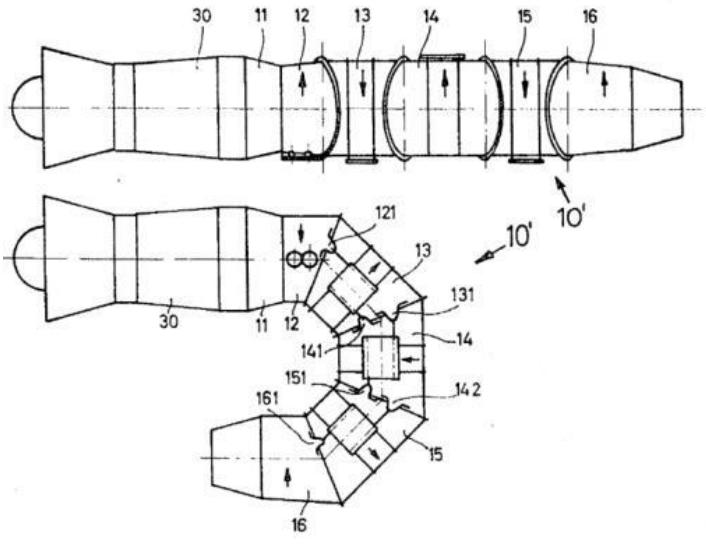


Figure. 3. Gerhard four-stage rotary nozzle structure

Later this year, Alexander [12] extended the maximum rotation angle of the nozzle to 90°, and added a reverse device to ensure the same speed rotation through the gear shaft.

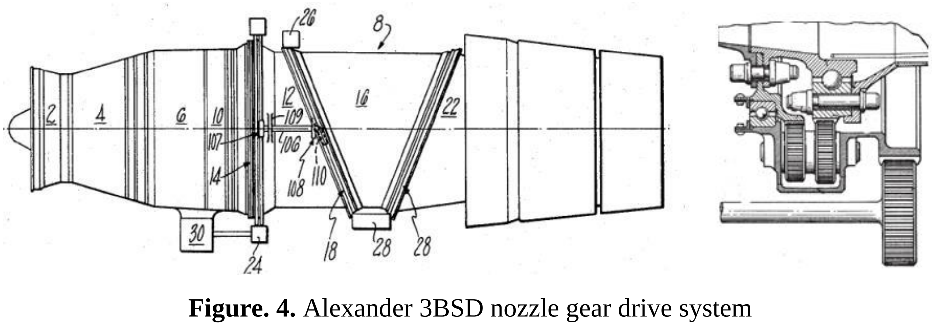


Figure. 4. Alexander 3BSD nozzle gear drive system

In 1972, Dudley [13] replaced the gear shaft and bevel gear assembly with a more compact ring structure.

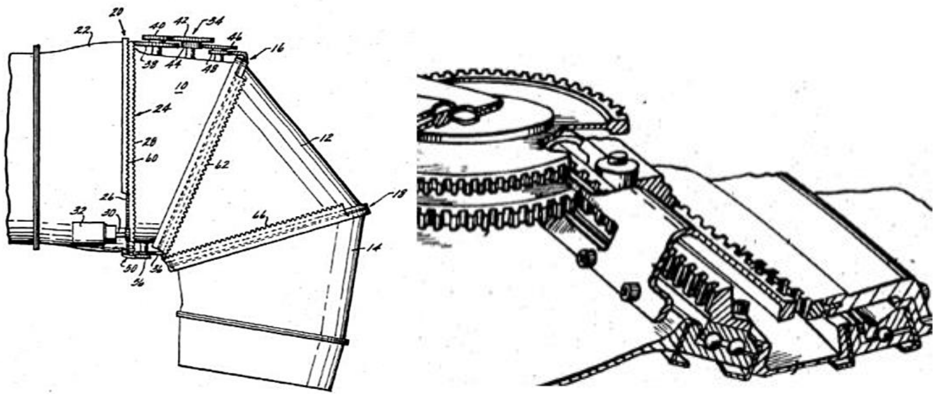


Figure. 5. Dudley 3BSD nozzle multi-gear drive system

In the scheme designed by Michael C. Roberts et al [14], two fixed pistons on the outer wall of the inner tube and the fixed piston cylinder on the inner wall of the outer tube were divided into three circular arc independent spaces. The rotation of the inner tube relative to the outer tube is achieved by the valve body controlling the high-pressure fluid to push the floating piston.

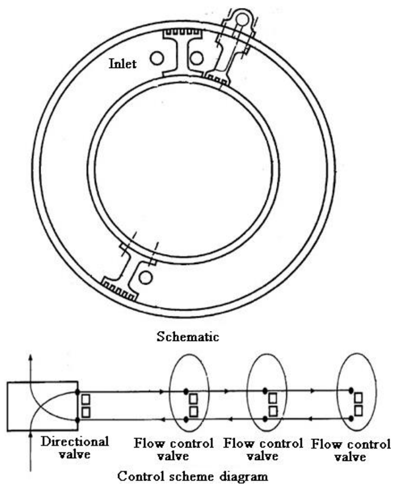


Figure. 6. Michael liquid / pneumatic thrust vector nozzle

The first practical application of the 3BSD nozzle was the main engine R-79V-300 of the former Soviet “Yak-141” SVTOL aircraft. When the short-range aircraft takes off, the nozzle rotates downward by 63°; when it takes off vertically, the nozzle rotates downward by 95° [15].

Figure. 7. "Yak-141" R-79V engine

The first duct of the F-35B is controlled by the flight control system to control the gear deflection of the rotating part of the aero-motor drive, while the second and third duct of the nozzle are driven by the hydraulic system, the 3BSD nozzle can be rotated from 0° to 95° in 2.5s [16].

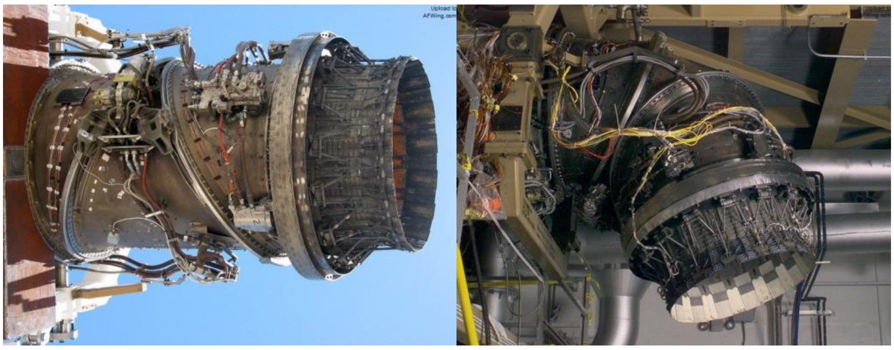


Figure. 8. F135-PW-600 engine assembly used in F-35B

China’s attention to S/VTOL aircraft started long time ago. In 1969, 601 institute included S/VTOL flapping variable-wing aircraft into special research projects. China's new round of S/VTOL aircraft pre-research has been carried out for at least a decade, but when compared with foreign research, domestic research on 3BSD nozzles started late, and the research level is low which mainly focus on the verification of the principle of S/VTOL aircraft aimed at F-35B in scientific research institutes and universities.

The 3BSD nozzle developed by Northwestern Polytechnical University [3] drives three ducts through three sets of motors to achieve vector rotation around three axes.

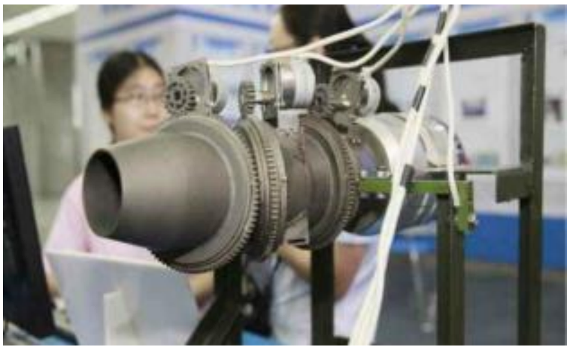


Figure. 9. 3BSD nozzle of Northwestern Polytechnical University [3]

Tsinghua University [17] has manufactured the largest S/VTOL demonstration named THU-F-35B in China. The nozzle rotary drive system adopts the first domestic “8” font-type precision cable drive, transmitting torque in the form of friction to drive the nozzle to the desired angle and change the direction of deflection. Through optimisation of the structure, the number of minimum drive motors required to deflect the 3BSD nozzle thrust vector is reduced by one compared with conventional single-stage drives.

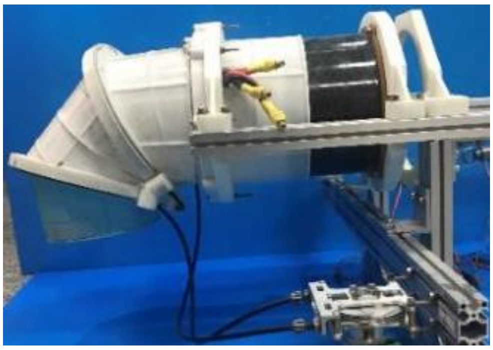


Figure. 10. 3BSD nozzle model of Tsinghua University

Lanzhou Jiaotong University [18] also adopts the cable transmission mechanism. The three drive motors are axially connected with reducer and fixed to the outer ring of each duct bearing through the end flange. As the driven wheel ring is uniformly opened with a wire rope guiding groove.

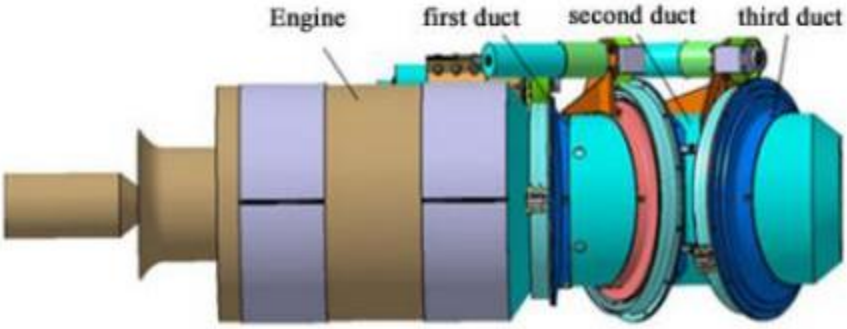


Figure. 11. 3BSD nozzle model of Lanzhou Jiaotong University

AVIC Engine has carried out the principle verification of the S/VTOL aircraft propulsion system. The 3BSD nozzle rotary drive scheme is shown in Figure 12:

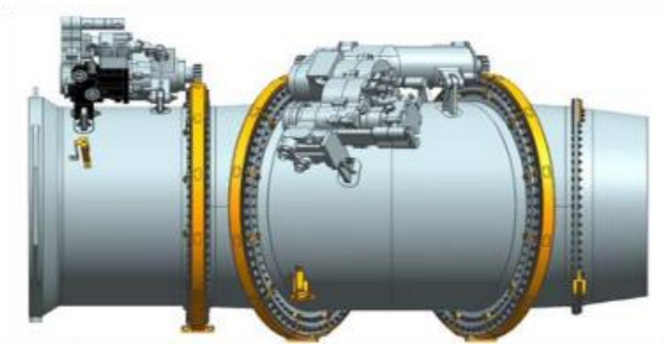


Figure. 12. 3BSD nozzle model of AVIC Engine Institute

4 Crucial Technical Analysis

4.1 3BSD nozzle rotary drive system working requirements

The saturation speed of the actuator is an important parameter of the aircraft. The 3BSD nozzle has a much longer travel range than conventional actuators. The rotation range for a given nozzle deflection command(δ_N , δ_{Nv}), Ω_1 , Ω_2 and Ω_3 is different [16]. Therefore, some actuators may saturate when other actuators dose not.

Firstly, the relationship between rate saturation speed of Ω_2 and δ_N is analysed. Secondly, Ω_3 is taken into account. Finally, Ω_1 and deflect directions are included. The second equation in the above equations can be rewritten as:

$$\cos^2(\theta)+\sin^2(\theta)\cos\Omega_2=\cos(\delta_\mathrm{N}/2)$$

By differentiating both sides, the relationship between the speed of Ω_2 and δ_N can be described as:

$$\dot{\delta}_N=\dot{\Omega}_2/d\Omega_2/d\delta_N$$

The function of $d\Omega_2/d\delta_\mathrm{N}$ is shown in Fig. 13.

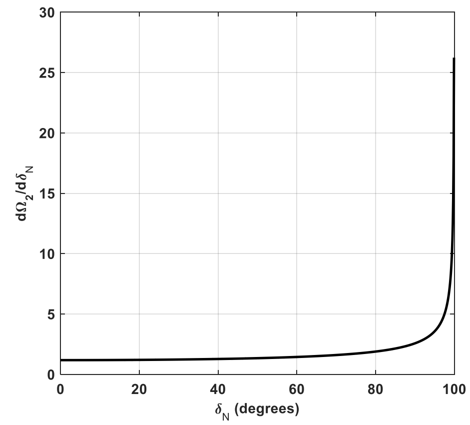
In order to satisfy the relationship between the rotation angle of each ducts, the thrust vector force and the maximum vector angle, the speed constraint imposed on the second rotation pair is:

$$max\left\{-1.8\dot{\Omega}_{1\min},\dot{\Omega}_{2\min},-\dot{\Omega}_{3\max}\right\}\le\dot{\Omega}_2\le min\left\{-1.8\dot{\Omega}_{1\max},\dot{\Omega}_{2\max},-\dot{\Omega}_{3\min}\right\}$$

Suppose δ_Ny is a constant, the equation could be deduced:

$$\dot{\Omega}_2 = \dot{\Omega}_1 d\Omega_2 / d\Omega_1$$

The function is shown in Fig. 14.



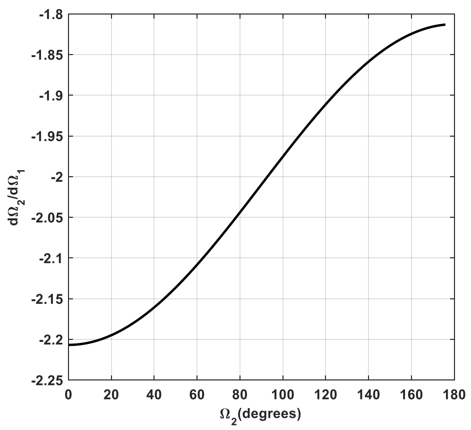


Figure. 13. $d\Omega_2 / d\delta_N$ curve **Figurer. 14.** $d\Omega_2 / d\Omega_1$ curve

Since the deflection speed of the 3BSD nozzle at different positions is limited, we can deduce that a relatively small rotation angle of Ω_1 can achieve a given lateral control force T_{Nv} . In normal flight mode, T_{Nz} close to 0 at most times, at this time, the corresponding δ_{Nv} will become infinity. Considering that the rotational angle is limited, the rotation angle of Ω_1 is 90°, which makes the flight control system unusable for lateral manipulation of the normal flight mode. Based on the above analysis, the 3BSD nozzle can provide lateral force/torque manipulation in hover and transition modes, while lateral force/torque manipulation is not available in conventional mode.
According to the existing research theory and results, it can be concluded that the 3BSD nozzle rotary drive system must meet the following conditions:
1.During the rotation of the nozzle, the thrust vector is maintained in a vertical plane;
2.The vector change process thrust is continuous;
3.The second rotating pair and the third rotating pair rotate in opposite directions at the same speed;
4.Complete the maximum vector angle change within 2.5s;
5.The axial distance of the nozzle is as short as possible;
6.The maximum vector change angle of the nozzle is ≥95°, and should not be greater than 100°.

4.2 Driving Mode

Table 1.3BSD nozzle rotary drive system form, characteristics and drawbacks.

Solutions	Research Unit	Characteristics	Drawbacks
gear	Jack	Pipe outer fixed gear	Pneumatic load acts on gear
	Carrol	the bearing is selected as the connecting part for the first time, and the synchronous rotating device is provided.	The mounting position of the motor causes one of the two output shafts of the motor to be bent
	Gerhard	The outer side is equipped with a gear for synchronously deflecting the upper and lower stages	axial dimensions increased resulted in aerodynamic losses
	Alexander	Change the maximum vector angle from 180° to 90°	the gear shaft is used as the linkage mechanism, unable to guarantee the axes of the segments in the same plane when the nozzle rotates,
	Dudley	Replace the gear shaft and bevel gear device with a ring gear structure	The use of planetary gear trains to increase the weight is not conducive to the lateral force of the nozzle
	NPU	Single-stage control, external ring gear drive	No synchronizing device, single-stage drive, integrated ring gear is not easy to repair
	AVIC Engine	Adjustable motor position	No synchronizing device, single-stage drive,

	Institute	according to nozzle vector angle	heavy weight of the drive system
Liquid/pneumatic	Michael C. Roberts	Cancel the sync device, the hydraulic/pneumatic drive is adopted to rotate nozzle	Leakage and inflammability of The hydraulic system; low transmission precision of pneumatic system due to the compressibility of air
	Yak-141	Single-stage control, external ring gear drive	Each segment is driven separately and the drive system is heavy
	F-35B	Combined with aviation steering gear and segmented hydraulic drive nozzle	The hydraulic system is heavy and the pipeline is complicated, and the intermediate pipeline needs to be bent.
Cable	LJU	Rotating the nozzle in the form of friction by the wire rope	No synchronizing device, single-stage drive, heavy weight of the drive system
	THU	the "8" font-type winding method, only one motor is used to control the deflection of the second and third of rotating pairs of the nozzle	This transmission method has only been tested on verification machine reduced in proportion and not sure whether it is suitable for real models with large weight.

The 3BSD nozzle rotary drive system not only needs to meet the requirements of the change of thrust vector angle of 3BSD nozzle, but also consider the overall aerodynamic performance, lightweight, high precision and heat resistance requirements of the aircraft. Comprehensively comparing the three development directions of 3BSD nozzle rotary drive system, we can find that although the hydraulic drive scheme has been applied to the F-35B and other models, there is still room for improvement in system complexity, heavy weight and fuel safety; as one of the most widely used transmission methods, gear transmission is the most mature technology. However, the problems of gear dynamic load, elimination of transmission clearance and integrated control connection of two and three stage nozzles still need to be solved. Flexible cable transmission scheme, as a new type of high precision and lightweight transmission scheme, is simple, efficient, accurate and reliable, without dynamic load. Although the actual application effect needs to be further verified, it is a good direction choice for the present domestic research stage.

4.3 Fly/push integrated control

The S/VTOL aircraft dynamics model is a constrained nonlinear system, and the actuators are redundant and heterogeneous. The transition process control requires the aircraft terminal state to meet the constraints, and the integrated control of the aircraft and power plant is complicated. Advanced S/VTOL aircraft power systems and jet airflow effects are more complex than traditional fighters, and the steering modes are more diverse, making linear controllers difficult to apply.

For the requirements of aircraft control and engine control, as shown in Figure 15, Pratt & Whitney [19] developed a multivariate control system based on the principle of partial dynamic transformation and model predictive control for the F135-PW-600 engine. This control system decomposes the complex, cross-linked and non-linear propulsion system dynamics model and presents the engine as a flight control virtual actuator. The entry is a module that decomposes and analyzes flight control commands. The multivariate limit module is used to determine that the target and limit are valid in the case of a given correction, and complete the corresponding dynamic transformation, nonlinear engine model and linearization. The engine is used to predict the variables that cannot be measured and to perform dynamic transformation. The estimator correction module is used to compare the feedback measurement and the model prediction results to indicate the mode and output deviation of the drive axis and compensate the calculation error of the model.

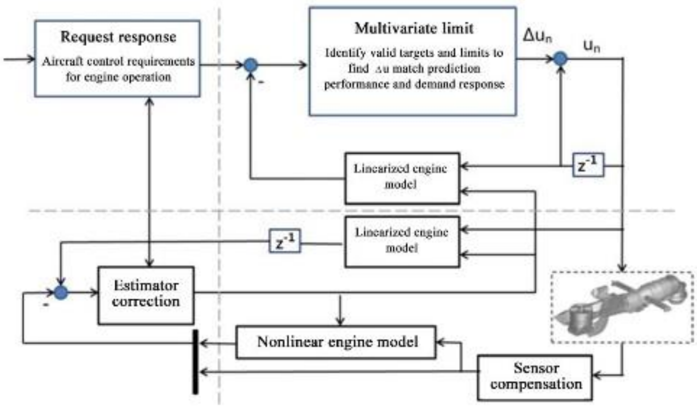


Figure. 15. Multi-variable control system of F135-PW-600 engine developed by Pratt & Whitney

The relationship between the three-duct nozzle angle and the vector thrust deflection angle is a monotonic strong nonlinear relationship, and the rotation sub-stroke is long during the use of the nozzle. Therefore, the study of the nozzle dynamic characteristics requires consideration of the three-stage actuator rate constraint and the rotation pair dynamic and rotational synergy.

Tsinghua University designs the nozzle coordination controller according to the inverse kinematics control law. The structure of the controller is shown in Fig.16. The dynamic allocation method is used to generate the tracking commands of the three actuators, Ω_{1c}, Ω_{2c} and Ω_{3c} the dynamic allocation method generates the three-level rotation sub-commands by nozzle inputting command δ_N and δ_{Ny}. The nonlinear kinematics relationship of the nozzle will bring difficulties to the design of the dynamic allocation method. This project replaces the control target and achieves the purpose of the variable nonlinear distribution assignment problem as a linear control assignment problem. Through the nozzle kinematics model, Ω_1 and Ω_2 are obtained, and the kinematic relationship" $\Omega_2 = -\Omega_3$ "is selected as the constraint equation. The optimization objective function for control allocation is:

$$J = \|\Omega_2(k+1) - \Omega_{2des}(k+1)\|_2 + \gamma\|\Omega_1(k+1) - \Omega_{1des}(k+1)\|_2$$

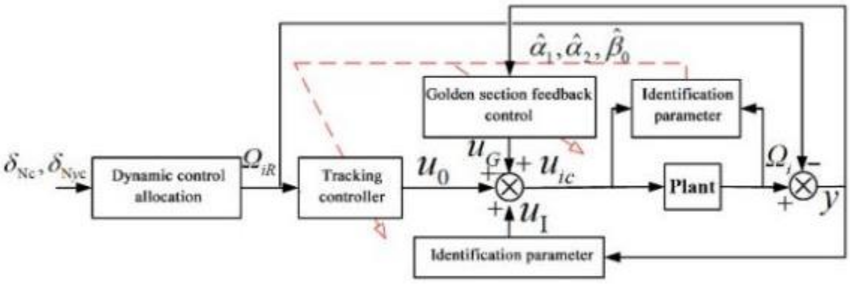


Figure. 16. Coordinated control method structure diagram

By solving the optimization problem, a three-stage rotation sub tracking instruction, Ω_{1R}, Ω_{2R} and Ω_{3R} can be obtained.

The principle of the nozzle coordination control method to achieve the system is shown in Figure 17. Among them, δ_{Nc} 、 δ_{Nyc} is the nozzle command signal, T_{Nc} is the engine thrust command signal, the DSP controller calculates the nozzle command signal and sends it to the nozzle servo through the command signal and the three-stage rotation of the nozzle. The location is sent to the control computer via the DSP controller and stored.

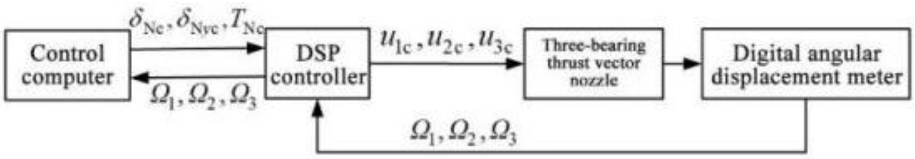


Figure. 17. 3BSD nozzle coordination controller implementation block diagram

4.4 Characteristic test

In addition to obtaining the data of lift, control response, flow field characteristics and other data of the aircraft through the S/VTOL aircraft before the test flight, the static and dynamic response tests such as deflection angle, deflection rate, driving torque and aerodynamics of 3BSD nozzle are carried out mainly through ground ignition test.

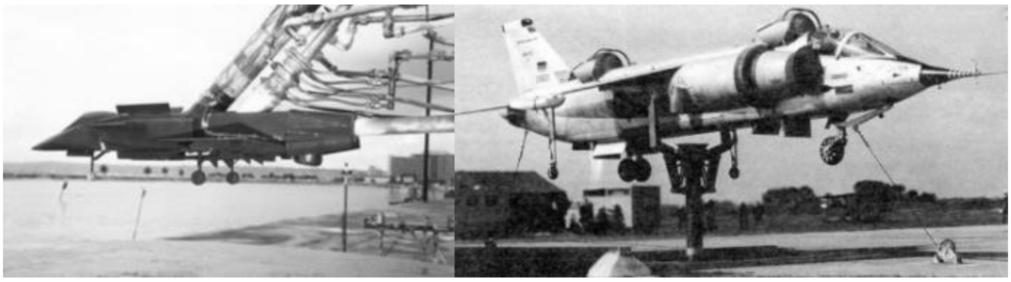


Figure. 18. Yak-141 hovering and VAK-191B ground mooring test

In order to test the dynamic characteristics of the nozzle and establish the dynamic model, the aeronautical vector nozzle test platform basically uses the high-precision six-component balance to record the vector thrust response. Firstly, the static thrust response of the turbojet engine is measured, and the engine dynamics model is established. The dynamic model of the engine is then identified by a dynamic force test. By measuring the static and dynamic response of the 3BSD nozzle separately, the nozzle static thrust deflection model and dynamic model are established in turn. Figure 20 is a schematic diagram of the test model.

The balance is divided into inner balance and external balance in the way of use [20]. When the vector nozzle is tested, there is a high-speed airflow inside, and there is no space for installing the inner balance, so only the external balance can be used. The external balance is mainly divided into two categories: mechanical balance and box balance. The mechanical balance has a series of problems such as complicated structure, intricate design, high cost, scattered sensor, difficult debugging and installation, has been gradually replaced by a box balance based on the strain principle. In the verification stage, the test of the small thrust engine is mostly horizontal; the horizontal balance is generally used to directly measure the main thrust and the lateral force to reduce the measurement error of the main thrust and the lateral force of the horizontal plane. At the same time, in order to reduce the size limitation and processing difficulty, the aviation vector nozzle test platform adopts a modular box balance that can be processed separately by each component.

The six-component balance consists of three parts: three-dimensional force sensor, floating frame and fixed frame. The fixed frame mainly supports the main thrust and lateral forces. There are various mounting standards on the floating frame to ensure accurate positioning of the engine and accurate installation of each component. When the aeronautical vector nozzle test platform is working, the vector thrust is decomposed into three mutually orthogonal forces and three directions of torque by a six-component box balance. In order to properly match the three component force loads of the three-dimensional sensor and minimize the influence of the load mismatch of the balance components, it is necessary to adjust the layout between the four three-dimensional sensors reasonably. At the same time, in order to ensure the measurement accuracy and stability, the sensitivity of the sensor elastomer is required to be high, and the sensitivity of the sensor is required to be large. The crucial is the selection of elastomer materials and structural layout design [21].

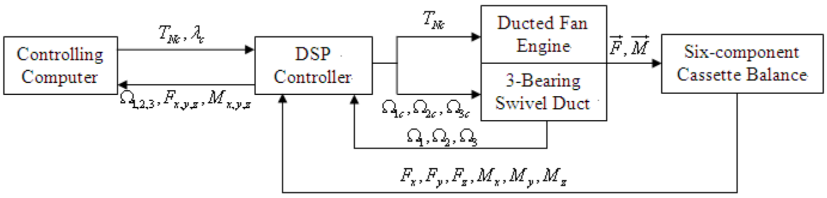


Figure. 19. Nozzle dynamics model

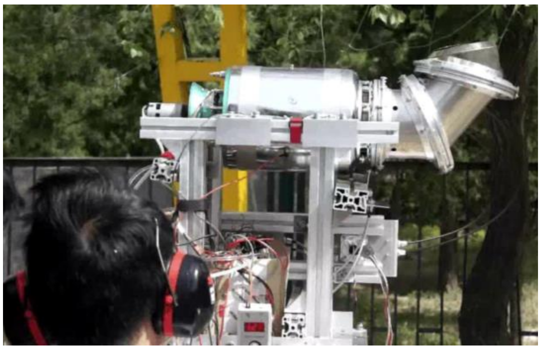


Figure. 20. Force test system

5. Conclusion

The difference between S/VTOL aircraft and conventional aircraft is mainly reflected in the field of power plant and aircraft-power plant depth coupling integration. These fields involve relatively new fundamental theoretical research and test technology. After decades of theoretical research, principle validation and engineering practice, the key technologies have been broken through, the test methods have been mastered, and the mature design and standard system have been established. Domestic research and principle experiments have been carried out in the field of S/VTOL aircraft power plant technology, but the research field is scattered and the technology maturity is low. The depth of research and the system integration are still difficult to meet the needs of development of short-distance take-off/vertical landing fighters. In general, power plant technology is still the bottleneck of China's development of S/VTOL aircraft. In order to speed up the development of S/VTOL aircraft power units, it is recommended that, on the basis of design and manufacturing of domestic aircraft and engine, materials technology, etc., a technical roadmap of S/VTOL aircraft power units must be , strengthen the aircraft demand and capability traction of engine, focus on the overall, core components and system design technology that restricts the power development, and realize the breakthrough of key technology integration.

6. References

[1] WANG X Y, ZHU J H, LIU K, ZHENG Y,Kinematic Modeling and Testing of 3-Bearing Swivel Duct Nozzle[J]. Acta Aeronautica et Astronautica Sinica 2014,35(4): 911-919
[2] Allen F J. Bolt upright: Convair's and Lockheed's VTOL fighters[J]. Air Enthusiast, 2007, 127: 13-20
[3] WANG Z X, LIU S, ZHOU L.Development and critical technology analysis on technology of short/vertical takeoff and landing fighter[J].Aeroengine, 2014, 40(4):1-6
[4] Bevilaqua P M. Joint strike fighter dual-cycle propulsion system [J]. Journal of Propulsion and Power, 2005, 21(5): 778-783
[5] Mason J R. F-35 S/VTOL Aircraft Performance Model Validation of Short Take-off Flight Test Data[R]. AIAA2013-4245
[6] Maddock I A,Hirschberg M J. The Quest for Stable JetBorne Vertical Lift:S/VTOL to F-35 S/VTOL[R]. AIAA2011-6999
[7] Saddington A J,Knowles K. Turbulence Measurement sin a Short Take-Off Vertical-Landing[J].Jouranl of Aircraft,2013,50 (2): 667-670
[8] Walker G P. Integrated Flight- Propulsion Control Development[R]. AIAA 2013-4243
[9] Jack Britt. Jet Pipe Arrangements For Jet Propulsion Engines[P]. US, 2933891, 1960
[10] Carroll E. Johnson. Variable Vectoring Nozzle for Jet Propulsion Engines[P]. US, 3260049, 1966
[11] Gerhard Kopp, Gero Otto Madelung. Swivelable Jet Nozzle, Intended Especially for Vertical Take-Off and Short Take-Off Planes[P]. US, 3443758, 1969
[12] Alexander Kurti, Richard W. Batt. Planetary Gear System Drive Mechanism[P]. US, 3485450, 1969
[13] Dudley O. Nash. Swivelable Jet Nozzle[P]. US, 3687374, 1972
[14] Michael C. Roberts. Apparatus for Moving Rotatable components. United States, B2, 7770379. Aug.10, 2010
[15] YUN Fei. Yak141-the first supersonic VSTOL fighter in world[J]. International Aviation,1991(12):28-30
[16] FANG Changde. Development research of aero-engine[M]. Beijing：Aviation Industry Press,2009：348-354
[17] Wang X Y,Zhu J H,Zhang Y J.Dynamics modeling and analysis of thrust-vectored S/VTOL aircraft[C]//The 32nd Chinese Control Conference,2013:1825-1830
[18] WANG X Y, YAN W H, XUE R R, ZHU J H and QI H.Design and Performance Analysis of a Scaled 3-Bearing Swivel Duct Nozzle[C] // The 2019 AIAA Propulsion and Energy Forum
[19] Ian A. Maddock, Michael J.Hirschberg. The Quest for Stable Jet Borne Vertical Lift:AS/VTOL to F-35 S/VTOL,AIAA 2011-6999
[20] HE W, TONG Z R, LI H B.Investigation of thrust valance for the single module scramjet[J].Journal of Aerospace Power.2010,25(10):2285-2289
[21] YU C A, LI P, WANG L.Design of elastic component of three-component strain gauge sensor[J].Chinese Journal of Sensors and Actuators,2012,25(3):333-337