ICAS 2021 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

RESEARCH ON ATTITUDE CONTROL AND CONSTRAINT SYSTEM DESIGN OF FULL-SCALE AIRCRAFT STATIC TEST BASED ON BARYCENTER

Zheng Jianjun[1,2], Wang Binwen[1], Zhu Lingang[3] & Tang Jiyun[1]

[1]Aircraft Strength Research Institute of China, Xi'an710065, China
[2]State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an, 710049, China
[3] Shanghai Aircraft Design and Research Institute, Shanghai 201210, China

Abstract

The attitude control theory and deficiencies of the full-scale aircraft static test based on the rigid body hypothesis are analyzed. Aiming at the huge elastic deformation characteristics of the aircraft after been loaded, the attitude control theory of the full-scale aircraft static test based on the barycenter is proposed, and then a six-degree-of-freedom displacement compensation control technology is further proposed from the perspective of technical realization. Taking a full-scale aircraft static test of a certain type of an aircraft as an example, the design of the full-scale aircraft constraint system adopting the six-degree-of-freedom displacement compensation attitude control technology is briefly described. With the measurable structure near the barycenter of the structure as the control center, the stiffness characteristics of the aircraft near the constraint point is analyzed, and the deformation of the constraint point relative to the control point under the test load is calculated. By means of counter-compensate the calculated displacement in the test load spectrum, and adding attitude monitoring sensors to measure the deformation in the preliminary test, the real-time displacement compensation amount of each degree of freedom is corrected to maintain the control point stable during the final test. The verification result indicates that the technical scheme is effective, the design result is reasonable, the control process is stable and reliable, and the attitude control of the full-scale aircraft has achieved the desired effect.

Keywords: Full-scale aircraft; Static test; Attitude control; Constraint system; Displacement compensation;

1. General Introduction

The primary task of aircraft structure design is to meet the static strength requirements, which means it must withstand various flight and ground design loads of the aircraft. In the process of the structural design, the building-block design verification idea, which is carried out from the element-level test, the component-level test, the module-level test to the full-scale structural test, is usually adopted[1-3]. To verify whether the aircraft structure meets the design static strength index requirements, the most direct and reliable method is to conduct a full-scale structure ground static strength verification test, which is called the full-scale aircraft static test[4-6]. The basic goal of the full-scale aircraft static test is to simulate as accurately as possible the structural loading of the aircraft in various extreme conditions that may occur during the service in a laboratory environment, and to verify whether the structure meets the specified strength requirements. All test conditions should be designed and verified with the target of approaching the extreme condition. The implementation of a full-scale aircraft structure static test requires multiple techniques such as loading, control, measurement, data analysis, and damage inspection[7-15]. Among them, the constraint is a vital technology. The function of the test constraint system is to adjust and control the attitude of the aircraft during the test, and simultaneously compensate the unbalance generated by the loading system. In order to ensure that the feedback of the test system is unique and can be monitored in real time, the static test constraint of the full-scale aircraft structure usually employs the static definite constraint, that is, a six-degree-of-freedom displacement constraint is set at a position where the full-scale aircraft structure has a strong bearing capacity to ensure that the position of the aircraft structure under the test remains unchanged, so that the test aircraft and test system are in a unified coordinate system [16-21]. In recent years, there has been a great number of research on the constraint method of the full-scale aircraft static test and the realization of related technologies, and certain research results have been obtained. However, most of these researches are based on the traditional six-degree-of-freedom static definite constraint method, focusing on solving some outstanding problems[22-24]. For the elastic large deformation aircraft structure, the traditional constraint methods and theories are no longer able to be employed due to the large deformation characteristics of the test aircraft after being loaded. Therefore, it is urgent to carry out corresponding theories, methods and technical research on such characteristics.

Based on the full-scale static test of a certain type of an aircraft, this paper analyses the stiffness characteristics of the test aircraft, and concludes that the aircraft structure has macroscopic characteristics of large-scale deformation. In accordance with the force characteristics of the aircraft structure, the aircraft attitude control theory based on the barycenter under the condition of elastic large deformation is proposed. Through the finite element analysis of the full-scale aircraft, the constraint system design method is formulated, and the attitude control technology of the displacement compensation of the constraint point based on the actual measurement was overcome. The project implementation verification indicates that the theoretical method is correct and the technical scheme is feasible, which provide significant reference value for follow-up similar experiments.

2. Constraint Benchmark Theory of The Full-scale Aircraft Static Test Based on Barycenter

2.1 The attitude control method of aircraft structure ground test based on rigid body hypothesis

Generally, the rigidity of the full-scale military aircraft is relatively large, and the relative deformation of the constraint point after the structure loaded is small. The small deformation has little impact on the test result, so that the structure in the interval of the constraint point of the aircraft can be approximated as a rigid body. For the constraint of the test aircraft, it is only necessary to design a six-degree-of-freedom static constraint at a convenient location to realize the function of uniquely controlling the displacement of the aircraft structure and monitoring the loading error of the test system.

The landing gear is a part of the aircraft structure that can withstand large concentrated loads and is convenient for constraint. The typical method of constraint design is to respectively set three vertical hinged constraint, two heading hinged constraint and one lateral hinged constraint, or two lateral hinged constraint and one heading hinged constraint at the wheel cores of the three landing gears. Thus, statically and steadily constraining the six-degrees-of-freedom of the full-scale aircraft. A typical full-scale aircraft structure constraint design scheme is shown in Figure 1.

Normally, the landing gear of the aircraft is located close to the fuselage of a place with a high rigidity. Especially in the design of military aircraft, the strength requirements, configuration characteristics and high whole-aircraft rigidity cause little impact on the deformation of the loaded structure, so the loading error because of the relative deformation of constraint is very small as well. Therefore, the constraint design based on rigid body can meet the requirements of the full-scale aircraft static test under the requirements of the test with greater structural rigidity and relatively lower attitude control accuracy.

The previous simplified methodologies are unsuitable because of the particularity configuration of some aircrafts. Take a certain type of civil airliner as an example, the main pillar of the main landing gear of the aircraft is hinged to the 5-ribbed rear beam of the left and right wings of the aircraft and the length of the main pillar exceeds 3 meters, which is a typical cantilever long-leg configuration. This configuration causes the landing gear wheel core to be affected by the superimposed deformation of the wing roll deformation, the wing pitch deformation, and the elastic deformation of the cantilever of the landing gear strut itself. Eventually, in the empty-weight state, the unilateral main landing gear wheel core has a deviation of 5mm from the actual coordinate, and the heading coordinate deviation is 20mm. As a result, if the displacement of the landing gear wheel core (constraint point) is fixed, and this point will be relatively deformed as the load of the whole aircraft structure increases. Under the condition that the displacement of the constraint point of the wheel core is unchanged, the wheel core will reverse the displacement of the aircraft and further change the attitude of the whole aircraft structure, thereby affecting the loading direction of other loading points, and ultimately seriously affecting the test accuracy. On the other hand, the "Static / Fatigue Test Process Error Control Regulations" specifies that the allowable horizontal limit deviation of the constraint point is 5mm. The excessive self-weight deformation will lead to the conventional constraint scheme to fail to meet the requirements of the relevant standards. Therefore, other potential solutions must be taken into consideration.

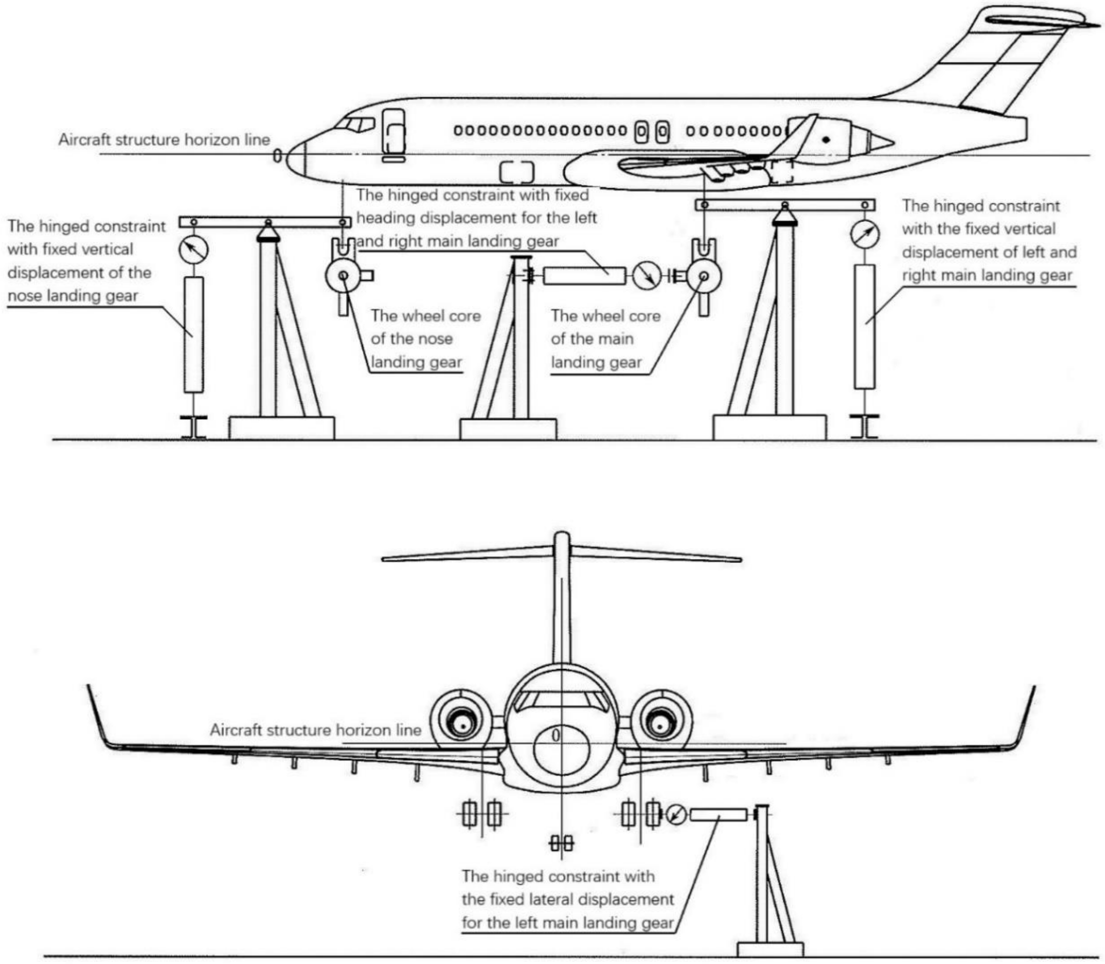

Figure 1 –Typical design schematic illustration of full-scale aircraft constraint

2.2 Elastic Deformation Theory of Aircraft Structure Based on Barycenter

Based on the barycentric deformation theory regards the aircraft structure as an elastomer. The coordinate system is established at the theoretical barycenter of the structure under the test case. The origin of the coordinate system is kept fixed while the rest of the structure is deformed during the test.

According to the basic mechanics theory of flight principle, the aircraft in the vertical direction is affected by the inertial force generated by the mass of the structure itself and the lift force mainly generated by the wing surface, which constitute a pair of equilibrium forces. In the horizontal direction, the aircraft is affected by the thrust of the engine and the aerodynamic resistance of the structure, and the two constitute a pair of balanced force systems. Because the aircraft fuselage usually adopts the frame and long quilted structure, the wing adopts the beam rib structure, so that the rigidity of the airframe structure in the vertical direction is low, and the deformation after the structure been loaded is large. In addition, the rigidity of the structure in the heading direction is large, and the deformation after the structure been loaded is small. Therefore, this paper grasps the main contradiction and mainly discusses the deformation characteristics of the structure in the vertical direction.

The typical force states of the aircraft structure in the vertical direction are shown in Figure 2.

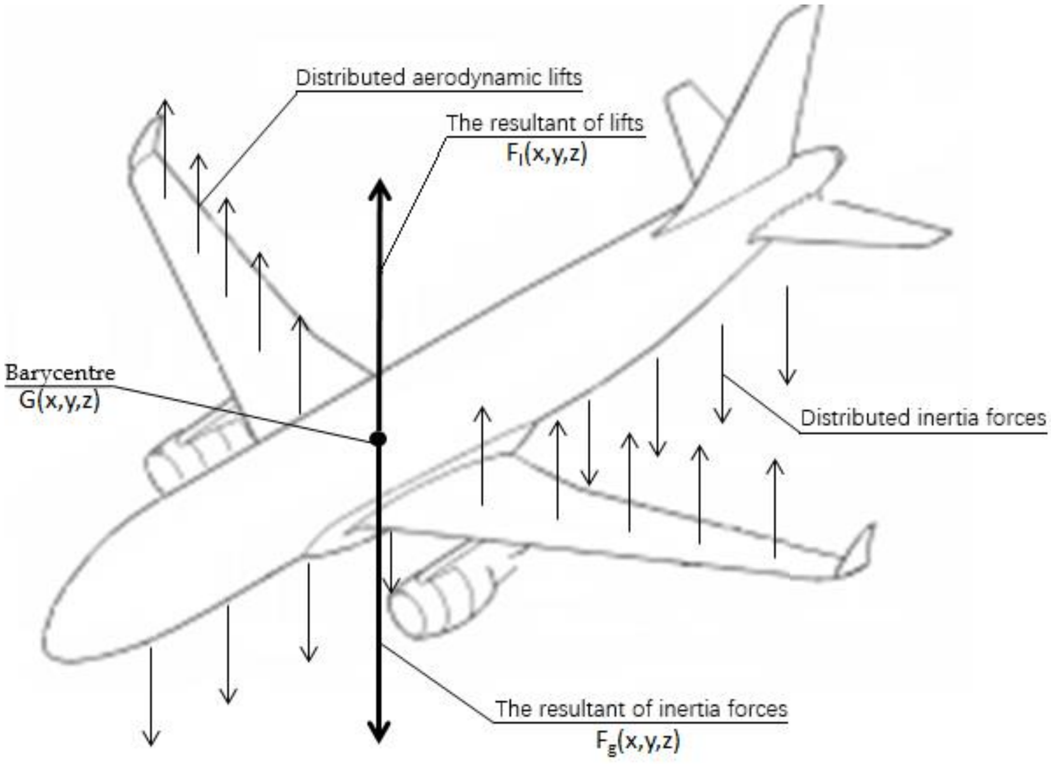

Figure 2 – Schematic diagram of vertical load balance in flight mechanics

The force states in the above schematic diagram can be expressed by the following formula.

$$M_{(x,y,z)} = \int_{v} \rho d_{v} \quad (1)$$

$$F_{m(x,y,z)} = M_{(x,y,z)} a \quad (2)$$

$$F_{l(x,y,z)} = \int_{s} p d_{s} \quad (3)$$

$$F_{m(x,y,z)} = F_{l(x,y,z)} \quad (4)$$

Where $M_{(x,y,z)}$ represents the total mass and center of gravity (structure, fuel, commercial load) of the aircraft, ρ is the density function of any position of the structure, $F_{m(x,y,z)}$ represents the resultant force of vertical inertial force of the aircraft, a refers to the vertical acceleration of the aircraft, and $F_{l(x,y,z)}$ represents the resultant force of the aerodynamic force of the aircraft.

It can be seen from the above basic principles that for any state in flight, the aircraft structure is based on the distributed mass of the aircraft, the vertical inertial load changes with the vertical acceleration, and the aerodynamic load changes based on the lift. The total load and the inertial force generated by the mass are balanced at the barycenter.

The deformation state of the aircraft structure is analyzed under the basic mechanical equilibrium state. The structure is centered on the barycenter, and the inertial loads and aerodynamic loads are balanced respectively at this point. If the barycenter of the structure is cut along the direction of the large components of the aircraft, each large component can be regarded as a continuously loaded cantilever beam with unfixed stiffness.

In accordance with the basic force balance formula of the structure, it can be concluded that in any state during flight, the load of the aircraft is based on the balance of the barycenter, and the deformation of the aircraft is based on the fixed barycenter at the state of the loaded cantilever.

2.3 The attitude control method of the full-scale aircraft static test based on the barycenter

There are three common characteristics in the input of the full-scale aircraft static test. Firstly, the test load is derived from the typical load-bearing extreme condition, that is, the case where the utilized envelope is the largest in all working conditions, and its load distribution follows two basic characteristics; The first one is that it is derived from the design use state, which approaches the real use state, and the second one is that the load distribution and resultant force follow the basic flight mechanics balance principle. Secondly, the test load comes from the typical working condition selected according to the load envelope, and the load distribution and resultant force follow the basic equilibrium principle of flight mechanics. Thirdly, the test load is applied on the basis of theoretical coordinates, and the loading equipment loads in a fixed and unified coordinate system.

The fundamental target of the full-scale aircraft structure static test is to simulate the actual force state and deformation state of the aircraft in use as realistically as possible. The load in the test originates from the use state, and the load application position is based on a fixed coordinate system. If the placement position and deformation state of the aircraft are also based on the actual use state, an accurate simulation of the real situation can be achieved.

Obviously, when the aircraft is placed on the basis of the six degrees of freedom of the barycenter under the conditions that the barycenter is fixed and deformation of the rest parts are released, the aircraft can be closest to the actual state.

The above analysis can be represented by the following logical closed-loop relationship diagram.

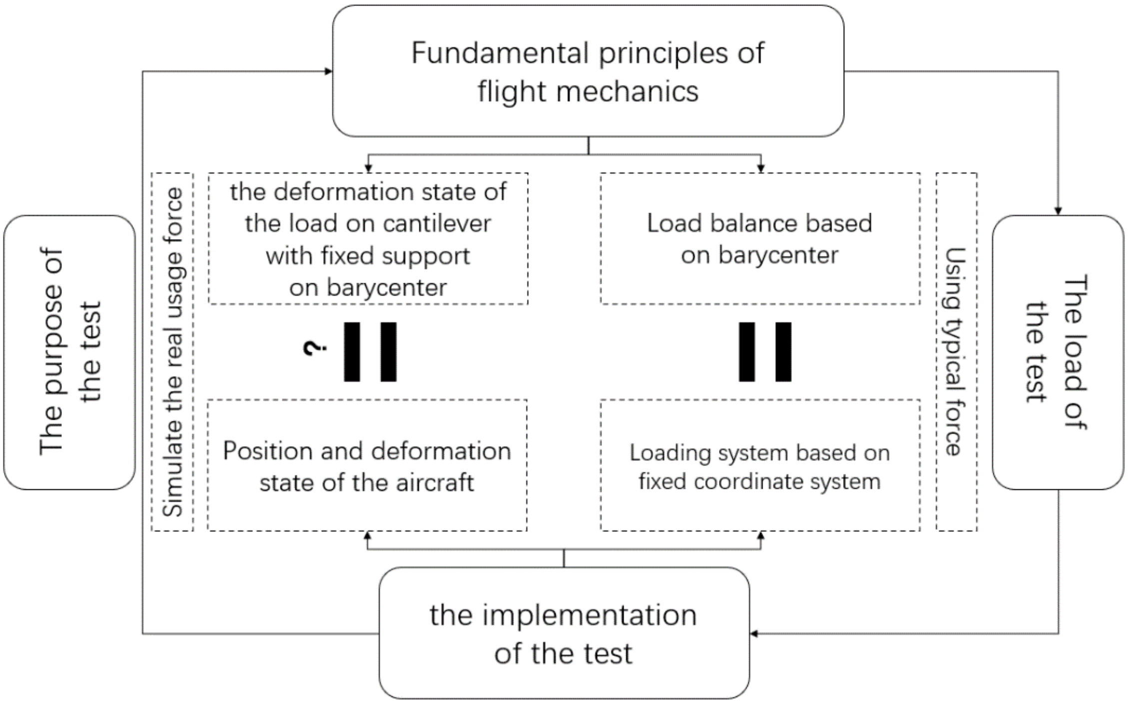

Figure 3 – Deformation logic of full-scale aircraft static test based on barycenter

The deformation theory of the full-scale aircraft structure static test based on the barycenter promotes the original rigid body constraint theory assumption to the elastic body constraint theory, and finds the constraint center. The finite element analysis under the guidance of this theory can more accurately guide the implementation of the test. In the static test of a full-scale aircraft structure, the position of the theoretical barycenter of the aircraft should be maintained constant, which means the six degrees of freedom that near the theoretical barycenter through external constraints are unchanged with the rest deforms freely in the test.

3. Design of Attitude Control System of Full-scale Aircraft Static Test Based on Barycenter

3.1 Profile of the research object

This paper selects the C919 aircraft as the research object. The aircraft has a wingspan of about 36 meters and a total length of about 30 meters. The weight of the test aircraft is about 20 tons. Because the aircraft is a large-scale airliner, the most typical test condition—2.5g stable pitching condition is selected as the typical analysis condition. Under the 150% of the limit load of this working condition, the upward load of the wing is about 270 tons, and the maximum deformation of the wing tip is about 3 meters, the tail deforms about 260mm vertically downwards, which is a typical elastic large deformation test condition. This load case mainly evaluates the strength performance of the main bearing structure of the wing. In accordance with the Chinese Civil Aviation Airworthiness Certification Standard, the criterion for passing the test is that the structure can withstand 150% of the limit load without damage[25]. According to the test program, the criterion for successful test implementation is that during the test is loaded step by step in light of the specified load level, the absolute value of the load error of a single constraint point is less than or equal to 5000N.

3.2 Analysis of Deformation Characteristics of test case

The physical structure point near the theoretical barycenter is selected as the theoretical constraint point, and the six-degree-of-freedom of this point are constrained in the finite element model of the full-scale aircraft structure. Applying the load according to the load distribution and size of the test implementation and releasing the displacement constraint of the actual constraint site. The theoretical displacements of the three landing gear wheel cores can be calculated to guide the design of the constrained structure. Taking the 2.5g full-scale aircraft stable pitching case as an example, the position of the constraint point G(x,y,z)=(21309,-500,0) selected by the full-scale aircraft finite element analysis is taken as the fixed control point. The computation results are exhibited in Figure 4. The computation results are utilized as theoretical support for the subsequent steps, and will provide predictive data support for the selection of constraint positions and the determination of constraint methods.

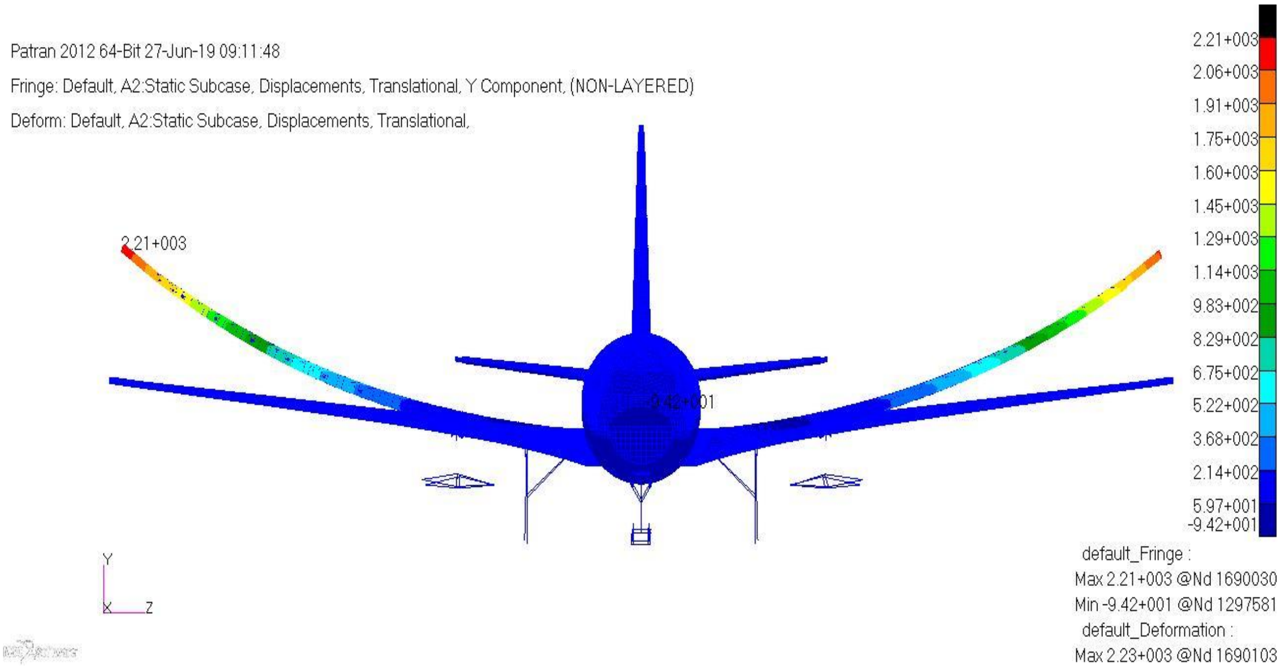

Figure 4 – FE result of 2.5g whole aircraft stable pitching case

3.3 Constraint location selection

The selection of constraint points requires comprehensive consideration of constraint stability, safety of constraints in unexpected situations, constraint adaptability, local strength, rigidity of the structure, etc. On this basis, the determination of the specific location also needs to combine factors such as the type characteristics of the flying mechanism, the key areas for the assessment of specific working conditions, and the theoretical analysis results of the assessment working conditions. This is a complex and engineering problem. There are often multiple constraint options for the identical aircraft in the identical evaluation condition. Based on the above principles, this paper selects the nose landing gear and the two main landing gear wheel cores as the attitude control points of the full-scale aircraft.

The displacements of the three landing gears in x, y, and z directions are,

$$\delta1(x,y,z)=(19.6,-65.7,-1.2) \quad (5)$$

$$\delta2(x,y,z)=(27.6,53.5,38.2) \quad (6)$$

$$\delta3(x,y,z)=(27.8,53.6,-38.9) \quad (7)$$

Where δ1 (x, y, z), δ2 (x, y, z), δ3 (x, y, z) represent the displacement in three directions of the nose landing gear, the left main landing gear and the right main landing gear by fix G point.

3.4 Determination of constraint method

On the basis of the above analysis results, the landing gear wheel cores to be constrained have large deformation in all three directions, and their values have exceeded the error limit specified by the standard. Therefore, the influence of the deformation on the attitude of the test aircraft must be considered when designing the structural constraints of the full-scale aircraft.

Taking the 2.5g full-scale aircraft stable pitching condition as an example, in accordance with the structural rigidity and load-bearing capacity characteristics, the vertical direction of the nose landing gear, the vertical direction of the left and right main landing gears, the heading of the left and right main landing gears, and the lateral direction of the right main landing gear are selected as the six-degree-of-freedom static constraint points. For the vertical displacement and pitch control of the aircraft, the nose landing gear deforms vertically by 65.7 mm, and the left and right main landing gears deform upwards by 53.5 mm. Due to the long heading distance between the nose and main landing gears, the pitch angle error of the aircraft caused by the vertical deformation is less than 1 degree, which has little effect on the test results. In addition, the loading points are all vertical loading points. It is evaluated that the change in angle does not affect the test implementation. Therefore, the nose landing gear adopts a hinged crowbar vertical displacement fixed restraint structure, and the left and right main landing gears adopt horizontal follow-up vertical hinged adjustable displacement constraints during the test. The vertical heights of the nose landing gear, the left and right main landing gear are preset during the test implementation, so that the vertical height and pitch angle of the aircraft can approach the theoretical state when the applied load is equal to the assessment load. For horizontal constraints, the calculation results suggest that the maximum heading displacement is 28mm, and the maximum lateral displacement is 39mm. For the heading displacement and lateral displacement, the hydraulic displacement closed-loop control load monitoring constraint method is adopted to compensate the heading and lateral deformation of the landing gears in real time during the loading process. For the roll attitude and yaw attitude control, the vertical direction of the left and right main landing gear of the roll attitude controlling and the heading of the left and right main landing gear of the yaw controlling are called symmetric deformation. As a result, roll deformation and yaw deformation are non-focused items, which can be compensated symmetrically using hydraulic displacement closed-loop control load monitoring and constraint method.

During the test installation, the vertical direction of the nose landing gear is constrained by conventional hinged crowbars, the vertical direction of the left and right main landing gears adopts the skateboard type horizontal follow-up vertical adjustable height load monitoring and constraint method, and the lateral position of the right main landing gear adopts a hydraulic position control force monitoring closed-loop control system. Besides, the fixed end in the height direction presets the installation height of the actuator to the theoretical height of the landing gear wheel core at the assessment point. The controllable mechanical deformation of each constraint point is set to be no less than 1.5 times the theoretical deformation to prevent the deformation from exceeding the predicted value in actual implementation and adjust.

The negative values of the heading of the left and right main landing gear and the lateral theoretical displacement of the right main landing gear are set as the active commands of the corresponding displacement control actuators in the test load spectrum. Assuming that the analysis is sufficiently accurate and the theoretical and actual states are identical, then the actual deformation of the aircraft should be consistent with the theory, and the displacement control command compensation at the constraint point just offsets its relative deformation, thus ensuring the stability of the attitude of the test aircraft.

The final constraint scheme of the full-scale aircraft working condition is shown in Figure 5.

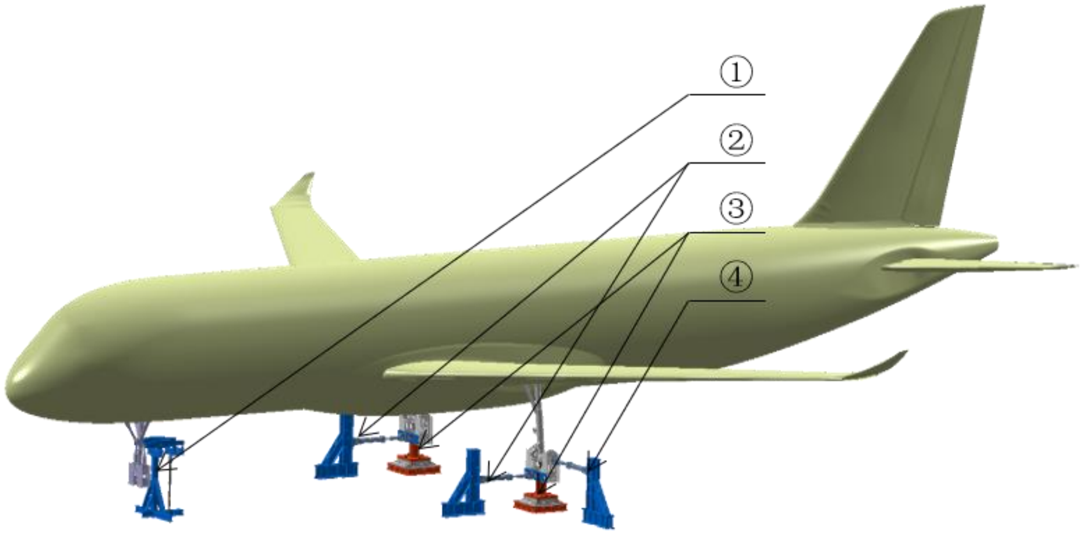

Figure 5 – Constraint scheme of 2.5g whole aircraft stable pitching case; 1. Crowbar hinged vertical constraint; 2. Hinged displacement follow-up control heading constraint; 3. Horizontal slide type follow-up vertical height adjustable vertical constraint; 4. Hinged displacement follow-up control lateral constraint

4. Active Displacement Compensation Technology for Constraint Points based on Actual Measurement

In fact, the constraint point displacement compensation attitude control technology based on theoretical analysis have certain errors. The reasons are as follows: 1. The analysis did not consider the test aircraft structure and equipment weight; 2. The test installation is not completely consistent with the theoretical analysis; 3. The test load application did not consider the error of the loading direction due to structural deformation.

In order to further improve the accuracy of the test constraints, real-time landing gear displacement compensation control technology is employed. that is, the aircraft heading displacement sensor is set on the nose heading to monitor the whole aircraft heading displacement. A vertical displacement sensor is set up in the vertical direction of the nose and the central wing to monitor the vertical and pitch attitude of the whole aircraft. And a lateral displacement sensor is set up in the lateral direction of the nose and the central wing to monitoring the lateral and yaw attitude of the whole aircraft. During the test, the attitude change of the aircraft is monitored synchronously throughout the process. In the preliminary test, the attitude change curve of the aircraft is obtained through the attitude monitoring sensor, the amount of attitude change is linearly accumulated until the assessment load is reached, and the displacement at the constraint point is back-calculated through the geometric relationship. This value is added to the pre-set displacement control command value through computation, and the preliminary test is performed again until the attitude of the test aircraft remains stable during the preliminary test.

5. Verification Results and Discussion

The displacement data of the aircraft attitude control sensor in the pre-test of the 2.5g full-scale aircraft structure in stable pitch conditions is shown in Figure 6. From Figure 6, it can be seen that the values of left and right main heading are small, and the pre-trial displacement is controlled within 1mm. However, these results are all unidirectional deviations and can be further adjusted appropriately. The lateral displacement of the right main starting point is relatively large, reaching 4.8mm, and it is difficult to meet the requirements for continued loading. Therefore, the amount of compensation must be modified. According to the geometric relationship and the proportion of the load series, the amount of the displacement compensation for the aircraft attitude control actuator is: The left and right main heading stacks 3mm respectively, and the right main heading stacks 12.5mm laterally.

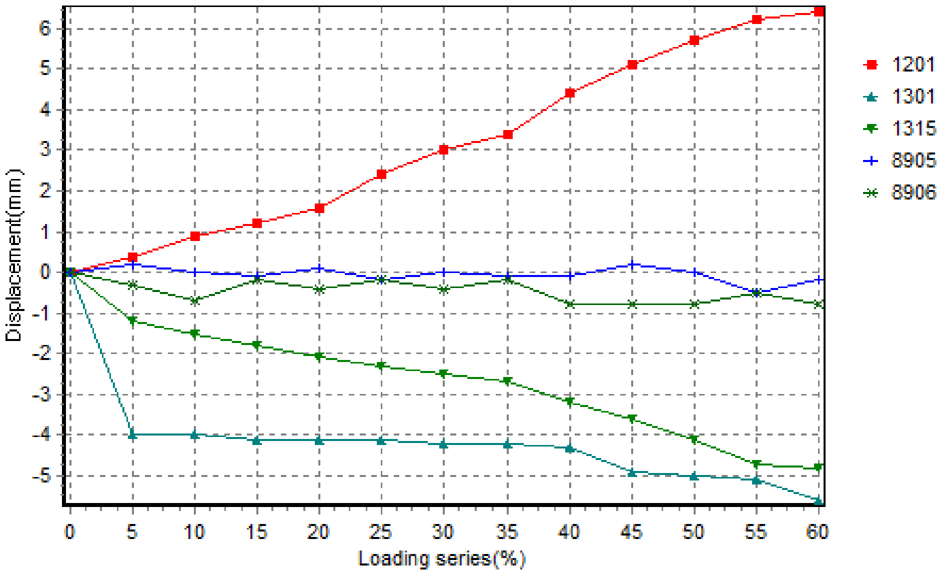

Figure 6 – Posture change of the first 60% limit load pretest on 2.5g whole aircraft stable pitching case; 1201. 1 frame vertical; 1301. 1 frame lateral 1315. Central wing lateral; 8905. Left main landing gear upper heading; 8906. Right main landing gear upper heading

In the final ultimate load test, the monitoring displacement of the aircraft attitude is shown in Figure 7.

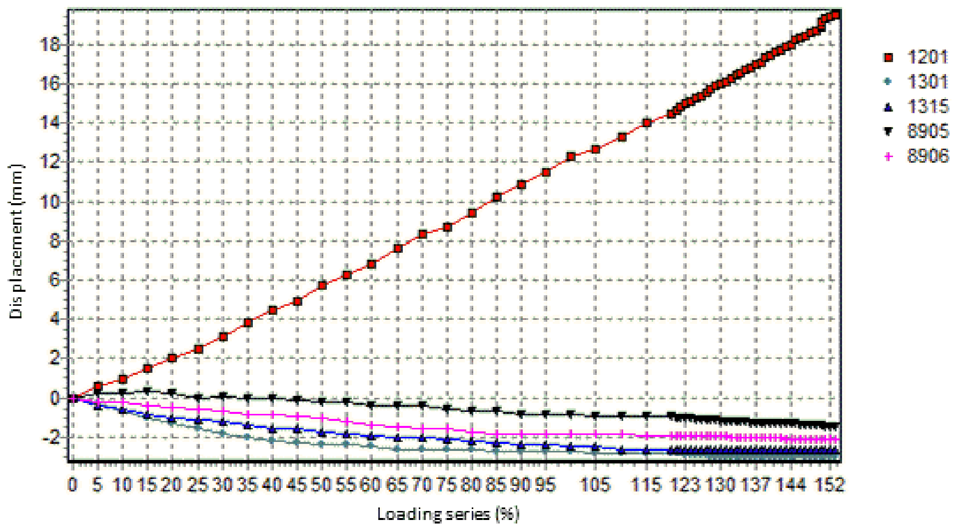

Figure 7 – Posture change of the last 150% limit load test on 2.5g whole aircraft stable pitching case; 1201. 1 frame vertical; 1301. 1 frame lateral 1315. Central wing lateral; 8905. Left main landing gear upper heading; 8906. Right main landing gear upper heading

It can be seen from Figure 7 that the displacement monitoring data of the 153% limit load test is linear and valid, which means it can reflect the overall attitude of the test aircraft. The value of the overall displacement is small, which meets the requirements of the attitude control.

6. Conclusion and Discussion

This paper introduces the design concept of the full-scale aircraft constraint based on the rigid body hypothesis, analyzes the structural rigidity and load capacity characteristics of the aircraft C919, find the problem that the rigid body hypothesis cannot meet the test requirements. Then proposes the structural deformation theory of an aircraft with the barycenter as the control center by means of basic theoretical analysis. Taking the full-scale static test of the aircraft C919 as an example, through finite element analysis, overall scheme design, test pre-test and other stages of analysis and testing, the real-time active displacement compensation attitude control technology is finally proposed. Discuss, the displacement monitoring data can be directly connected to the control system, the monitoring data and attitude adjustment formula can be established through the geometric relationship, and the compensation amount can be adjusted in real time according to the actual measurement results. However, this control method is not reliable due to the lack of reliability of the displacement sensor. The sensor can be easily affected by external physical interference when the pull-out rope of the displacement monitoring part is exposed without protection. For the sake of safety, this control method is not employed. It can be further taken into consideration after the reliability of the sensor is improved.

7. Contact Author Email Address

Zheng Jianjun: ylzjj_86@163.com

8. Copyright Statement

References

[1] 孙侠生, 齐丕骞. 民用飞机结构强度刚度设计与验证指南[M]. 北京: 航空工业出版社, 2012:374.
Sun Xiasheng, Qi Peijian. Design and verification guide of Strength and stiffness in civil aircraft structure [M]. Beijing: Aviation Industry Press, 2013: 357 (in Chinese).

[2] 郑建军, 唐吉运, 王彬文. C919飞机全机静力试验技术 [J]. 航空学报, 2019; 40(1):522364-522364.
Zheng Jianjun, Tang Jiyun, Wang Binwen. Static test technology of C919 full-scale aircraft structure [J]. Acta Aeronautica et Astronautica Sinica, 2019, 40(1): 522364 (in Chinese).

[3] 中国飞机强度研究所. 航空结构强度技术[M]. 北京: 航空工业出版社, 2013:357.
AVIC Aircraft Strength Research Institute. Aircraft structure strength technology[M]. Beijing: Aviation Industry Press, 2013: 357 (in Chinese).

[4] 强宝平. 全尺寸飞机结构试验技术 [J]. 航空科学技术, 2012(6):10-13.
Qiang Baoping. Evaluation of full scale aircraft structure strength test technology [J]. Aeronautical Science & Technology, 2012(6):10-13 (in Chinese).

[5] 张兆斌, 李明强, 李健. 大型运输机全机静力试验总体规划与实施研究 [J]. 航空科学技术, 2015(10):25-27.
Zhang Zhaobin, Li Mingqiang, Li Jian. Research on comprehensive planning and implementation for full-scale static test of large transporter [J]. Aeronautical Science & Technology, 2015, 26(09): 25-27 (in Chinese).

[6] Mohaghegh M. Validation and certification of aircraft structures[C]. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. Austin, Texas, 2005.

[7] 王育鹏, 裴连杰, 李秋龙, 等. 新一代战斗机全机地面强度试验技术 [J]. 航空学报. 2020, 41(6): 523482.
Wang yupeng, Pei Lianjie, Li Qiulong. et al. Full-scale Aircraft Strength Test Technology of Next Generation Fighter[J]. Acta Aeronautica et Astronautica Sinica, 2020, 41(6): 523482 (in Chinese).

[8] Shim J-y, Lee S-G, Ahn S-M. Kc-100 full-scale static test system [J]. Aerospace Engineering and Technology, 2012; 11.

[9] 卓轶, 吕媛波, 张文东. 飞机结构强度试验中拉压垫加载技术研究 [J]. 科学技术与工程, 2016; 16(2):244-248.
Zhuo Yi, Lv Yuanbo, Zhang Wendong. The re-search of tension/compression pad load technique in structure strength test [J]. Science Technology and En-gineering, 2016; 16(2):244-248 (in Chinese).

[10] 刘玮, 滕青, 刘冰. 基于地板结构的机身双层双向加载技术 [J]. 航空学报, 2018; v.39(05):136-143.
Liu Wei, Teng Qin, Liu Bing. Double deck bi-directional loading technology based on airliner cabin floor structure [J]. Acta Aeronautica et Astronautic Sinica, 2018, 39(5): 221712 (in Chinese).

[11] 任 鹏，杜 星. 飞机强度试验大曲率弧形曲面结构加载技术及其应用[J]. 科学技术与工程, 2021, 21(10) : 4255-4259.

Ren Peng,Du Xing. Application of large curvature curved surface structure loading technology in aircraft strength test [J]. Science Technology and Engineering,2021,21(10) : 4255-4259 (in Chinese).

[12] 王海, 杜峰, 杜星, 等. 大面积连续压向载荷模拟施加技术研究[J].航空科学技术, 2020, 31(08): 16-21.

Wang Hai, Du Feng, Du Xing, et al. Research on large area continuous compression load simulation technology [J].Aeronautical Science & Technology,2020,31(08):16-21 (in Chinese).

[13] 杜星, 王鑫涛. 阀控非对称缸单向加载方法研究 [J]. 机床与液压, 2017; 22:028.

Du Xing, Wang Xintao. Unidirectional loading method for valve controlled asymmetric cylinder [J]. Machine Tool & Hydraulics, 2017; 45(22):105-108 (in Chinese).

[14] 韩凯, 贺谦, 左佳. 飞机强度试验异常应变数据诊断研究 [J]. 工程与试验, 2016; 56(4):7-12.

Han Kai, He Qian, Zuo Jia. Study on Fault Diagnosis for Abnormal Strain Data in Aircraft Strength Test [J]. Engineering & Test, 2016; 56(4):7-12 (in Chinese).

[15] Zhao Hongwei, Duan Shihui, Feng Jianmin. A preliminary study on application of closed-loop cross compensation control in accelerated fatigue testing[C]. 33rd AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2017.

[16] 王鑫涛，杜星． 多轮多支柱起落架飞机强度试验支持系统研究及应用[J]. 机床与液压, 2020, 48(9) : 95-98.

Wang Xintao, Du Xing. Research and Application of Strength Test Support System of Multi-wheel and Multi-strut Landing Gears Aircraft [J]. Machine Tool & Hydraulics, 2020, 48(9) : 95-98 (in Chinese).

[17] 刘权良, 尹伟, 夏峰. 飞机结构静强度试验支持方案的确定 [J]. 航空科学技术, 2012(5): 32-35.

Liu Quanliang, Yin Wei, Xia Feng. The Determination of Support Scheme for Aircraft Static Strength Verification Test [J]. Aeronautical Science & Technology, 2012(5):32-35 (in Chinese).

[18] 刘玮, 郑建军. 大型客机结构试验主起落架随动加载技术[J]. 航空科学技术, 2020, 31(12): 42-47

Liu Wei，Zheng Jianjun. Self-adaptable loading technique for main landing gears in structural test of large airliner [J]. Aeronautical Science & Technology, 2020, 31(12): 42-47 (in Chinese).

[19] 王孟孟, 刘冰, 王高利. 大型飞机起落架载荷修正方法研究. [J]. 应用力学学报. 2021, 38(02), 708-714.

Wang Mengmeng, Liu Bing, Wang Gaoli. Research on load modification method of large aircraft landing gear [J]. Chinese Journal of Applied Mechanics, 2021, 38(02): 708-714 (in Chinese).

[20] 杜 星, 冯建民, 贺谦. 全机结构试验起落架随动加载技术研究[J]. 科学技术与工程, 2017, 17(2) : 288-292.

Du Xing, Feng Jianmin, He Qian. Self-adaptable loading technique for undercarriage in full scale aircraft structure test [J]. Science Technology and Engineering, 2017, 17(2): 288-292 (in Chinese).

[21] 王鑫涛，杜星. 飞机结构强度试验差动式加载方法研究[J]. 机床与液压, 2020, 48(10) : 80-83.

Wang Xintao, Du Xing. Research on Differential Loading Method for Aircraft Structural Strength Test [J]. Machine Tool & Hydraulics, 2020, 48(10) : 80−83 (in Chinese).

[22] 王高利, 唐吉运. 全尺寸飞机结构试验约束点载荷误差分析及优化 [J]. 工程与试验, 2014; 54(2):42-46.

Wang Gaoli, Tang Jiyun. Error analysis & optimi-zation for constraint point load of full scale aircraft test [J]. Engineering & Test, 2014; 54(2):42-46 (in Chinese).

[23] 王鑫涛, 杜星. 飞机结构强度试验应急载荷限定系统 [J]. 航空学报. 2020, 41(2): 223332.

Wang Xintao，Du Xing． Emergency Load Limited System for Aircraft Structural Strength Test [J]. Acta Aeronautica et Astronautica Sinica, 2020, 41(2): 223332 (in Chinese).

[24] 刘 冰, 王孟孟, 郑建军, 等. 大型飞机主起落架连接区静力试验误差控制技术[J]. 科学技术与工程，2021, 21(10) : 4249-4254.

Liu Bing, Wang Mengmeng, Zheng Jianjun, et al. Error control technology in static test on connection area of main landing gear of large aircraft [J]. Science Technology and Engineering, 2021, 21(10) : 4249-4254 (in Chinese).

[25] 中国民用航空规章-第25部-运输类飞机适航标准: CCAR-25-R4[S]. 中国民用航空总局政策法规司, 2016.

China Civil Aviation Regulations - Part 25 - Airworthiness Standards for Transport Aircraft: CCAR-25-R4[S]. China Civil Aviation Administration Policy and Regulation Department, 2016(in Chinese).