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Design and implementation of rigid-flexible coupling for a half-flexible single jack nozzle

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Abstract The aerodynamic design of a rigid-flexible coupling profile is the decisive factor for the flow-field quality of a supersonic free jet wind tunnel nozzle, and its mechanic dynamic features are the key for engineering implementation of continuous Mach number regulations. To fulfill the requirements of a free jet inlet/engine compatibility test within a wide simulation envelop, both uniform flow-fields of continuous acceleration and deceleration are necessary. In this paper, the aerodynamic design methods of an expansion wall and machinery implementation plan for the half-flexible single jack nozzle were researched. The profile control in nozzle flexible plate design was studied with a rigid-flexible coupling method. Design and calculations were performed with the help of numerical simulation. The technique of axial free stretching of the flexible plate was used to improve the matching performance between the designed elasticity profile and the theoretical one, and the rigid-flexible coupling structure was calibrated by wind tunnel tests. Results indicate that the flexible plate aerodynamic design method used here is effective and feasible. Via rigid-flexible coupling design, the flexible plate agrees with the rigid body very well, and continuous Mach number changes can be achieved during the tests. The nozzle's exit flow-field uniformity meets the requirements of China Military Standard (GJB).

1. Introduction

From the research and development history of aero-engines, it is indispensable to simulate an aircraft's real operating environment in ground tests, especially in recent years, with the continuous development of new fighters.[1–3] During an aircraft's acceleration, deceleration, or large maneuvering, dynamic performances are always the key point and the major difficulty in the design and assessment of aircraft. Moreover, as the requirements of a wind tunnel are various for testing

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the operation envelopes of different engines development, the simulation capability of a ground test facility is demanded to be more advanced and flexible. To resolve these dilemmas and to make improvement on an aircraft's performance, it is crucial to build a jet wind tunnel with continuous variable Mach numbers,[4–6] which can perfectly reproduce the true flow pattern and dynamic response of a real flow-field at the engine inlet during aircraft maneuvers or acceleration and deceleration operations.[7] Furthermore, during the development of advanced aero-engines, some key technologies must be studied and verified via free jet tests with a variable Mach number wind tunnel, such as the dynamic responses of turbine-based combined cycle engine performance[8] and variable cycle engine performance during an operation mode transition.[9]

Today, free jet testing devices with a flexible nozzle have been widely adopted in Western aviation developed countries.[10–12] In China, the vast majority of supersonic wind tunnels use a fixed geometrical nozzle with a fixed exit Mach number.[13] Recently, Ref.[14] introduced the usage of a domestic advanced full-flexible nozzle, and Ref.[15] researched the performance of a half-flexible multi-jack nozzle. However, no literature about design and calibration of half-flexible single jack nozzles has been reported yet. Compared with the aforementioned two flexible nozzles, a half-flexible single jack nozzle has the following advantages. (1) Due to the single jack structure, the Mach number can be adjusted quickly to simulate an aircraft's dynamic incoming flow during acceleration and deceleration operations. (2) Without the limitation of supporting collaborative arrangement of multiple points, various nozzle driven modes can be adopted, and even be set outside of a wind tunnel, so as to provide possibilities of attitude simulation. (3) The simple mechanical structure of a half-flexible nozzle lets it cost less than one-tenth of that of a full-flexible nozzle. However, due to the reduction of the jack, the nozzle profile's aerodynamic performance, mechanical property, regulation performance, and so on, are required strictly, so as to assure that a flexible profile nozzle with an appropriate geometry has equivalent flow-field quality to a fixed nozzle. The key points to ensure the flow-field quality at the nozzle exit are as follows: (1) Compatible design of a rigid-flexible coupling and aerodynamic profile; (2) No concentrated moment is allowed at the end-to-end connection point of the flexible plate during the variation of the Mach number, and the curvature of the rigid-flexible coupling profile should be continuous; and (3) The synchronism and harmony between rigid-flexible coupling mechanism adjustment and flow-field dynamic response must be ensured.

In this paper, the aerodynamic design and dynamic analysis of a rigid-flexible coupling profile which was applied to a half-flexible single jack nozzle structure was studied by using a theoretical calculation and numerical simulation method. The flow-field was calibrated via wind tunnel tests, and the design method and flow-field quality were verified.

2. Design calculations

2.1. Nozzle design

In 1955, Rosén first proposed the prototype of an adjustable nozzle.[16] The half-flexible single jack nozzle profile is composed of a fixed profile plate and a flexible plate with linear thickness, and its principle of regulating its Mach number was introduced in Ref.[17]. A comparison between the nozzle designed in this paper and a conventional half-flexible single jack nozzle is shown in Fig. 1. As can be seen, the present nozzle has the following characteristics:

(1) The longitudinal height compensation improves the axial free deformation at the end of the flexible plate. Rapid regulation of the nozzle's exit Mach number has been achieved at the expense of the loss of the boundary correction capability at the nozzle end. In addition, coupling performance of the rigid-flexible profile is improved.
(2) The rotating mechanism is replaced by an arc rail around the fulcrum N of the fixed plate, in order to resolve technological problems during the transition process, such as subsonic starting or transonic acceleration.

2.2. Elastica inverse problem

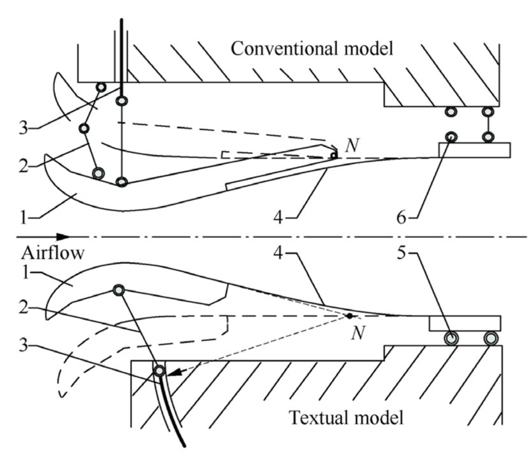
The core issue in the design of a flexible nozzle is the elastica inverse problem, also known as the elastic large deflection problem,[18] which means to ensure a coupled flexible profile to be consistent with a theoretical aerodynamic profile.

For our half-flexible single jack nozzle, the thickness of the plate is increased linearly along the flow direction to ensure that the curvature of the aerodynamic profile changes continuously, as shown in Fig. 2.

The change of the flexible plate thickness is given by

$$h = h_0(1 + \beta\xi) \quad (1)$$

where β is the variable thickness factor of the flexible plate, h is the thickness at the flexible plate end, h_0 is the thickness at the flexible plate starting point, and ξ is a dimensionless relationship, i.e., $x = \xi L$, in which x is the abscissa of the flexible plate, and L is the total length of the flexible plate.



1—Fixed plate, 2—Seal plate, 3—Drive rod, 4—Flexible plate, 5—Axis compensator, 6—Longitudinal compensator

Fig. 1 Airstream models of half-flexible single jack nozzles.