論 文 の 内 容 の 要 旨

論文題目：

Unsteady Aerodynamic Characteristics of Compressor Oscillating Cascade in Transonic Flow with Shock Waves

(衝撃波を伴う遷音速流における圧縮機振動翼列の非定常空力特性に関する研究)

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In the field of commercial turbofan engine, the fan and compressor technology improves to satisfy the demands of high propulsive efficiency and energy saving, and the trend of increasing bypass ratio is obvious. Among the design solutions, more complex 3D blade structure and higher load cause the more complicated and unsteady flow field, while larger fan size and more weight saving cause blade rigidity decreasing. In such situation, blade vibration is more likely affected by the surrounding unsteady flow field, which can cause the aeroelastic instability. Among the aeroelastic phenomena in turbomachinery, cascade flutter is a phenomenon of self-exciting vibration which affects the stability of the machine to great extent. It often has disastrous consequence and difficult to predict theoretically. In the fan and front compressor stages, the cascade is under transonic flow condition where the flutter phenomena are more complicated due to the interaction among blade motion, shock wave and flow separation. The deeper understanding and more effective predicting method of cascade flutter phenomena are essential for engine performance promotion.

Due to the existence of lots of unknown phenomena in cascade flutter, the integration of experimental measurement and numerical simulation is expected for research development and analysis method establishment. The knowledge of unsteady aerodynamic force and unsteady pressure distribution acting on the blade surface is significant for flutter interpretation. Such data can be obtained by conducting wind tunnel experiment with oscillating cascade where the real phenomena of pressure fluctuation are grasped by using conventional sensors, such as pressure transducers and strain gauges. However, only discrete pressure distribution can be acquired which is insufficient to understand the unsteady behaviors of local flow phenomena, such as shock wave and flow separation. As the 2D spatial distribution of unsteady pressure on blade surface is strongly needed, another pressure sensor which is fast-response pressure-sensitive paint (PSP) is highly expected to be a powerful tool for obtaining detailed information of unsteady surface pressure due to its capability of non-contact, quantitative pressure measurement with fast time response and high spatial resolution for complex aerodynamic flows. CFD is another effective way for flutter research based on the verification by experimental results, which mainly includes time-domain or frequency-domain URANS method and FSI method. Under the condition of small amplitude when blade deformation is already known and can be evaluated linearly, URANS method is effective with enough accuracy.

In view of above mentioned background, this research is aimed to conduct the steady and unsteady aerodynamic characteristics analysis of compressor oscillating cascade in transonic flow with shock waves, and accumulate basic knowledge on the mechanism of transonic compressor flutter phenomena.

The experimental and numerical approaches were applied in this research. Experimental object was a compressor cascade consisted of 7 DCA blades (named as blade -3~3 in flow direction) in a transonic flow which was generated by a transonic wind tunnel. This cascade was applied to simulate the relative velocity condition of transonic rotor cascade. The downstream throttle valve in the wind tunnel was used for adjusting cascade shock pattern by changing the static pressure ratio (P.R.). The central blade 0 can be oscillated in translational mode, with reduced frequency range to be 0.0078~0.0547. Anodized aluminium pressure-sensitive paint (AA-PSP) technique was applied to the measurement of steady and unsteady pressure distribution on blade surface. Then, 3D RANS simulation of the oscillating cascade was conducted for comparing with PSP results and obtaining more flow details. Finally, the flow phenomena and aerodynamic stability of the cascade were analyzed comprehensively.

In order to realize unsteady pressure measurement on oscillating blade surface, an “Automatic blade positioning” image processing technique was proposed based on Hough transformation method. Pressure results of transonic compressor cascade acquired by AA-PSP technique were validated by conventional methods and compared with CFD results. AA-PSP shows quantitative capability in steady pressure measuring and qualitative capability in unsteady pressure measuring.

The steady flow fields with different P.R. were measured and calculated. Pressure results obtained by PSP and CFD have good accordance with conventional methods. The total aerodynamic force acting on blade is almost in linear correlation with P.R.. Then, the detailed pressure distribution on blade surface and more flow details were analyzed. The shock wave structure in current transonic compressor cascade is classified into 4 types: choked flow/ double shocks/ merged shocks/ detached shock patterns with the P.R. increasing. Under lower P.R., the shock pattern consists of one oblique shock wave induced by blade leading edge and one passage shock wave in flow passage. There exist two low pressure areas on suction side (S.S.). With the increasing of P.R., the downstream low pressure area becomes small and finally disappears. The two shock feet also merge with each other gradually near S.S.. The mass flowrate variation with P.R. was also calculated to illustrate the flowrate characteristics of cascade under different shock pattern.

Then, based on the known steady flow field, the unsteady aerodynamic characteristics of oscillating cascade in translational mode were analyzed. Three central blades under double shocks pattern and merged shocks pattern were measured by PSP. The corresponding CFD calculations with

11 blade passages were also conducted by using steady calculation results. The unsteady pressure phenomena are mainly caused by the movement of shock waves responding to blade oscillation, and also affected by 3D wall effects. CFD shows a satisfactory accordance with the PSP results in capturing the dominant unsteady pressure phenomena induced by shock wave movement and interpreting the unsteady pressure evolution with P.R.. The direction of shock waves movement in neighboring flow passages of oscillating blade under double shocks pattern is almost reverse comparing to the merged shocks pattern, which is explained by different mass flowrate sensitivity. The displacement of passage shock foot responding to blade oscillation under merged shock pattern is quite larger than double shocks pattern. As to the farther blades, the blade oscillation has stronger influence on the downstream blade passages than upstream ones. Furthermore, more interval working conditions were calculated by CFD. The amplitude of unsteady aerodynamic force has a tendency of accelerated growth with P.R. increase, comparing to the linear increasing averaged aerodynamic force. The mechanism of unsteady pressure propagation were analyzed based on CFD results. At blade mid-span, the unsteady pressure is mainly induced by shock waves and propagates with increasing phase delay from alternating 0° and 180°.

Finally, aerodynamic stability of transonic compressor oscillating cascade was analyzed based on influence coefficient method. Shock waves with the 3D wall effects were considered as the dominant factors of aerodynamic instability. In low reduced frequency range, the oscillating cascade is possible to be aerodynamically unstable. The maximum positive unsteady aerodynamic work point was analyzed which is in most unstable state. In low P.R. range (choked flow/ double shocks pattern), the unsteady aerodynamic work is of relatively small value and sourced from two shock waves, tip clearance flow and P.S. supersonic area; in high P.R. range, the unsteady aerodynamic work is of relatively large value and dominated by the passage shock wave. In detached shock case, P.S. is in subsonic condition and the leading edge also has server positive work influx. With the increasing of reduced frequency, the maximum unsteady aerodynamic work and corresponding IBPA decrease. In high reduced frequency range, the cascade is stable in all IBPA range, while there are still some obvious positive work influx located at passage shock wave area at maximum unsteady aerodynamic work point. By considering all the working conditions of current cascade, the leading edge area (0-0.3x/c) is vulnerable to be affected by large unsteady aerodynamic force with large positive unsteady aerodynamic work influx, which is also the thinnest part of the blade profile.

As described above, the fast response PSP technique and CFD simulation were applied effectively to acquiring unsteady pressure distribution on blade surface of a transonic compressor oscillating cascade. The unsteady aerodynamic characteristics of oscillating cascade were illustrated by shock waves analysis. Moreover, the cascade stability of various working conditions was analyzed comprehensively. Here also proposes a possible prospect of this study. In this study, the unsteady pressure measurement conducted by PSP was mainly focused on low reduced frequency

(<0.06) range, which is limited by the vibration characteristics of the blade made of aluminum alloy. Due to the time response capability of AA-PSP, it can capture high frequency pressure fluctuation larger than 1 kHz. Furthermore, the flutter phenomena at high reduced frequency range are more complicated and essential for comprehensive understanding of their mechanisms. So, the knowledge of 2D spatial unsteady pressure distribution for high reduced frequency cases is strongly expected for the improvement of flutter study and CFD verification. Either selecting another solid blade profile or increasing the natural frequency of DCA blade is a possible solution.