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INVESTIGATION OF FLOW CONTROL OVER THE SUPERCRITICAL AIRFOIL BY TANGENTIAL JET BLOWING AT TRANSONIC SPEEDS

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Abstract

The results of calculation and experimental studies of efficiency of the compressed air jet tangential blowing through a slot nozzle over the supercritical airfoil upper surface to suppress the shock-induced boundary layer separation and the buffet at transonic speeds are presented. Numerical simulations were carried out on the basis of the unsteady Reynolds averaged Navier-Stokes (URANS) equations. Experimental studies of the tangential jet blowing were performed in the transonic wind tunnel T-112 of TsAGI. Results show that the jet blowing moves the shock downstream, increases lift, suppresses flow separation under shock foot and delays buffet onset.

1 Introduction

One of the most important and complicated problems of the modern aerodynamics is the problem of increasing flight cruise speeds of subsonic civil transport aircraft. The main obstacle on this way is an abrupt rise of the wave drag and intensification of shock-induced flow separation. Moreover, unsteady interference of shock-wave with the separated flow leads to the aircraft buffeting.

As a consequence, a delay in buffeting onset could potentially lead to improved aerodynamic performance characteristics. One of the ways to delay buffet is the concept of flow control.

Different devices were investigated as the means of buffet control. Mechanical vortex generators (VGs) and special mechanical trailing edge device (TED) which can change rear loading of the airfoil were studied in [1]. Fluidic VGs (air-jet VGs) as well as fluidic TED (jet near the trailing edge blown normally to the airfoil pressure side) were studied in [2]. It was shown that mechanical and fluidic VGs were able to delay buffet onset in the angle-of-attack domain by suppressing separation downstream of the shock. The effect of the fluidic TED was different, the separation was not suppressed. In this case, the buffet onset was not delayed in the angle-of-attack domain, but only in the lift domain.

The effective way to overcome the problem is the concept of active flow control at high subsonic Mach numbers by means of the tangential jet blowing over the wing [3, 4]. To suppress shock-induced flow separation the jet of compressed air is blown from a slot nozzle tangentially to the upper surface of the wing in the area of the shock-wave position in front of the expected flow separation.

In the present study, buffet control method by tangential jet blowing is investigated. The jet of compressed air is blown continuously from the small slot nozzle tangentially to the upper surface of the wing in the region of shock location to reduce the shock-induced separation. Experimental studies of the flow over transonic supercritical airfoil with active flow control by tangential jet blowing was carried out in the transonic wind tunnel T-112 TsAGI with the square test cross-section of 0.6x0.6 m^2 and the length of 2.59 m.

Numerical simulations were carried out using the unsteady Reynolds averaged Navier-Stokes (URANS) equations.

2 Numerical simulation

Supercritical airfoil P-184-15SR with the thickness of 15% and chord length of c=0.2 m is chosen for investigations as a baseline configuration (Fig. 1). Reynolds number based on free-stream parameters and chord length is equal to $Re=2.6\times10^6$. To simulate the jet blowing, slot is added at x-coordinate X_j=60% of the chord with height of h=0.15 mm. This slot is generated by removing small part of the airfoil (Fig. 2).

RANS and URANS equations are used for simulations. The calculations are carried out for the ideal compressible gas with laminar Prandtl number Pr=0.72. Laminar viscosity-temperature dependence is approximated by Sutherland law with Sutherland constant 110.4 K. Laminar-turbulent transition was fixed at x/c=0.15. In URANS simulations, SST model showed no buffet at all considered regimes so that Spalart-Allmaras (SA) model was used for simulations.

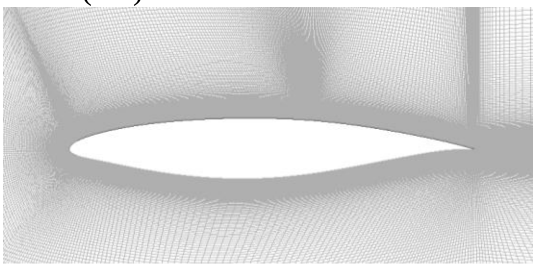


Fig. 1. Airfoil P-184-15SR and grid near the airfoil.

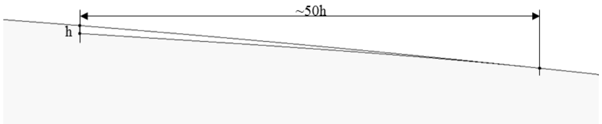


Fig. 2. Slot geometry at X_j=0.6.

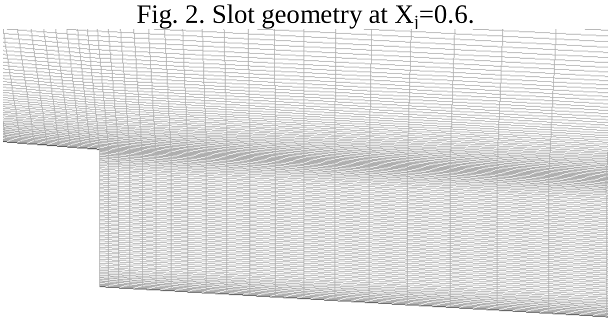


Fig. 3. Grid near slot nozzle.

Computational grid consists of approximately 200 000 cells. Grid nodes are clustered normal to the surface inside the boundary layer so that $Y_{+1}<1$. Grid near the slot nozzle is shown in Fig. 3. Grid convergence study showed that the grid size is sufficient for numerical simulations [3].

Numerical solutions are obtained using an implicit finite-volume method. The equations are approximated by a second-order shock-capturing scheme. Second order upwind scheme is used for spatial discretization of convective terms. Central-differencing scheme is used for diffusion terms. The second order time discretization is used for transient simulations. Dual time stepping scheme is used. Time step equals to $2\text{x}10^{-6}$ s with internal iterations converging up to the error $\sim10^{-6}$. Calculations with time step $1\text{x}10^{-6}$ s show that the results are independent on time step in this range.

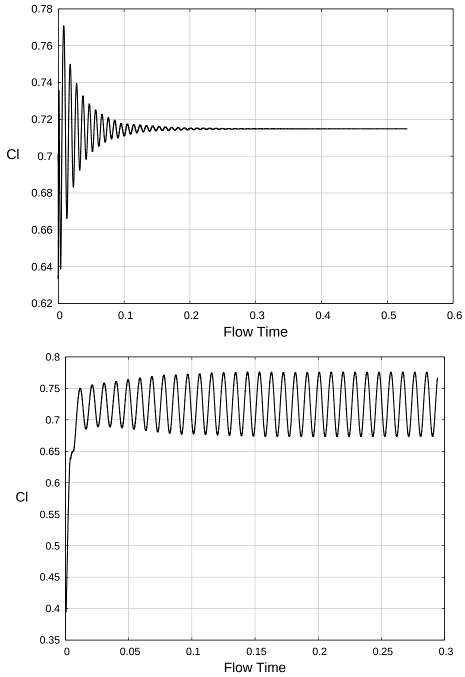
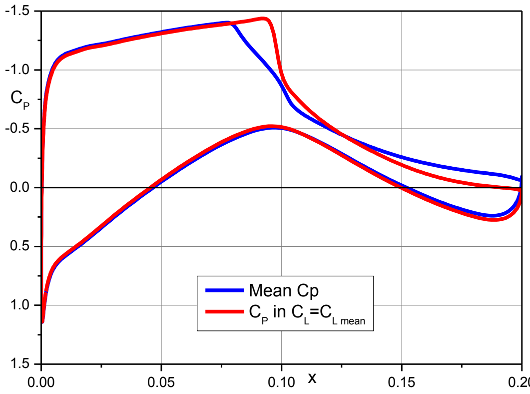
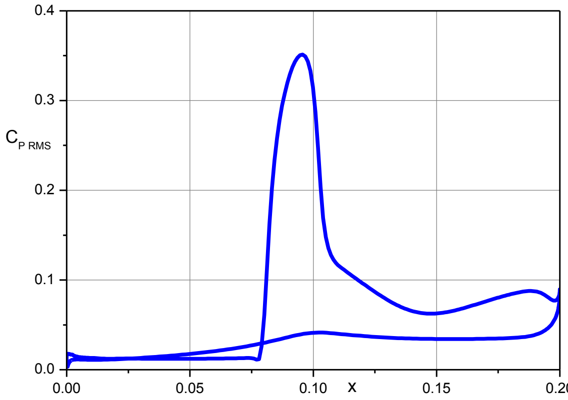


Fig. 4. C_L convergence history for regimes without (upper M=0.73, AoA=4°) and with buffet (lower, M=0.73, AoA=4.5°).

Examples of lift coefficient C_L convergence history for the case without and with buffet are shown in Fig. 4. It is seen that there is buffet at t α=4.5°. Buffet frequency varies from 99 Hz for M=0.72 and AoA=5° to 118 for M=0.74 and AoA=4.5°. Pressure coefficient C_p and root-mean-square (RMS) values of C_p pulsations are presented in Fig. 5 for M=0.73 and α=5°. Blue line corresponds to the time-averaged value of C_p while red line corresponds to the instantaneous C_p at the moment when C_L equals to the mean value of C_L. It should be noted that there is an essential difference between them. RMS values of C_p show that the shock wave oscillates approximately between x/c=0.38 and 0.55 for M=0.73 and α=5°.



a)



b)

Fig. 5. Mean and instantaneous Cp distributions (*a*) and RMS of Cp (*b*), M=0.73, AoA=5°.

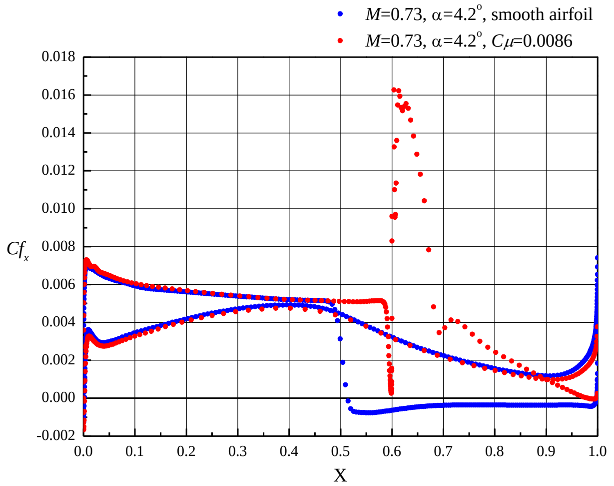


Fig. 6. X-component of skin friction coefficient: smooth airfoil and airfoil with jet blowing: M=0.73, AoA=4.2°; blue curve – smooth airfoil, red curve – jet blowing with Cμ=0.0086.

The jet is simulated by a boundary condition stated on the slot nozzle with corresponding jet momentum coefficient C_μ. The jet blowing position X_j/c=0.6 is placed slightly downstream of the shock position of the smooth airfoil (C_μ=0) which is not optimal. Jet blowing moves the shock downstream. It is seen in Fig. 6 where x-component of friction coefficient is presented for M=0.73 and α=4.2°.

The shock becomes stronger and wave drag increases while C_μ increases. Moreover, friction drag downstream of the shock increases while C_μ increases. There is a separation under the shock foot for the case of smooth airfoil. For the case with jet blowing there is no separation under the shock foot.

Figure 7 shows aerodynamic performance characteristics of the airfoil P-184-15SR with the tangential jet blowing for M=0.73. Aerodynamic forces were calculated without taking into account slot nozzle. Different jet intensities are considered.

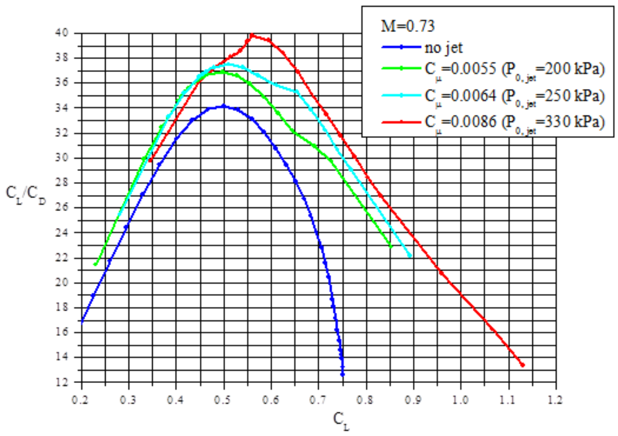


Fig. 7. Lift to drag ratio for different jet intensities, M=0.73, X_j/c=0.6.

It should be noted that the increase of C_μ leads to the increase of lift to drag ratio.

Lift curve for the case M=0.73 is shown in Fig. 8. Black curve corresponds to the case without jet blowing, while green curve corresponds to the case with weak jet blowing (C_μ=0.00069). Bars on the curves designate RMS values of oscillations. It should be noted that the deviation of lift curve from the linear regime is near α=2-2.5° while buffet onset regimes begin from α=4.2° (bars on black curve). Bars on green curve begin to grow from α=4.5°-5°. This trend shows that even weak tangential jet blowing delays buffet onset. Red curve of Fig. 8 corresponds to the case of relatively strong jet blowing with C_μ=0.0086.

There are no oscillations of C_L in this case and there is no buffet. One can conclude that tangential jet blowing delays buffet.

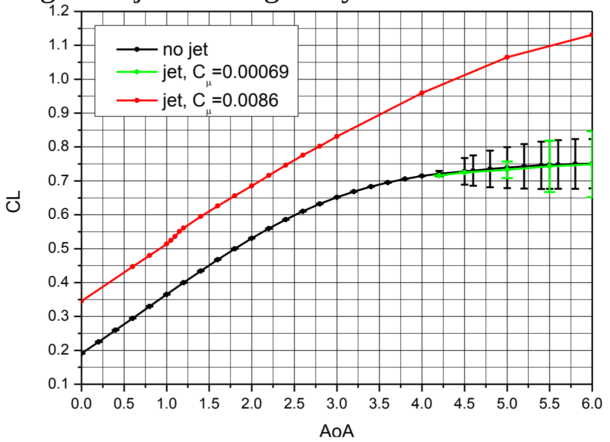


Fig. 8. Lift curve for M=0.73 with and without tangential jet blowing

3 Experimental investigations

The experiments were carried out in the transonic wind tunnel T-112 TsAGI. T-112 has the following characteristics: square test cross-section – 0.6x0.6 m^2; length of test section – 2.59 m; side walls are solid; top and bottom walls were with the perforation of 23%; stagnation temperature – environmental temperature T_0=287 K; stagnation pressure – 1 atmosphere; Reynolds number based on free-stream parameters and chord length (200 mm) – ~2.6×10^6; standard run duration – 300 s.

A model of the airfoil is performed in the form of rectangular wing with the same cross section (Fig. 9) and located between the side walls of the test section. The side walls in the region of the model installation have optical windows, which enable optical measurements of the flow around the model by means of Schlieren-type images.

The model contains the equipment for the tangential jet blowing and various measurements performed during WT tests. The following measurements were carried out: shadow-type visualization of flow over the upper surface; pressure taps on the upper (20 points) and bottom surfaces (15 points); unsteady pressure pulsations measurements on the upper surface (10 points); wake investigations using the rake to measure stagnation pressure profile; pressure (16 points) and pressure fluctuations (3 points) measurements on wind tunnel walls.

Fig. 9. T-112 TsAGI transonic wind tunnel with the model; view from the leading edge.

P-184-15SR airfoil was chosen as the baseline configuration as in the numerical simulations. The wing model has the thickness of 15%, chord length – 200 mm, span – 600 mm. For these tests, the model was equipped with a slot nozzle for tangential jet blowing. The slot was located at 60% of chord and had height of 0.15 mm. Range of total pressure of the blown jet is P_{0jet}=1.5; 2; 2.5; 3 atm. Special pylons for compressed air supply was developed near side walls (Fig. 9).

Boundary layer transition was triggered at 15% of the chord on the upper and bottom airfoil surfaces.

The typical dependency of pressure coefficient C_p on the model surface corresponding to the different jet intensities is shown in Fig. 10. Figure 11 presents RMS values of Cp pulsations while Fig. 12 shows total pressure distribution in the wake downstream of the model in the central cross section in vertical direction. One can see that the increase of a jet stagnation pressure moves the shock wave downstream and leads to a better trailing edge C_p recovery.

It should be noted that there are no pressure pulsation sensors at $0.5<x/c<0.65$. The maximal value of RMS C_p can be in this region and thus it is impossible to estimate the maximal values of RMS C_p and the region of high pulsations. The increase of RMS Cp appears due to the shock wave generation. Peak of pulsations follows the shock wave. In the case with jet blowing, P_{0jet}=2.5-3 atm, C_p at trailing edge shows that there are no flow separations. In these cases peaks of RMS values can relate to the unsteadiness in the region of the slot location due to the jet blowing.

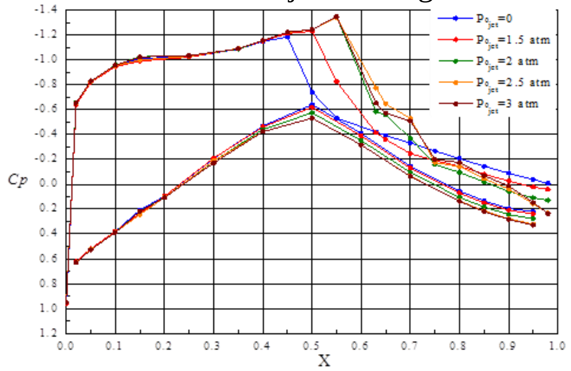


Fig. 10. Pressure coefficient distributions for M=0.76, α=6°.

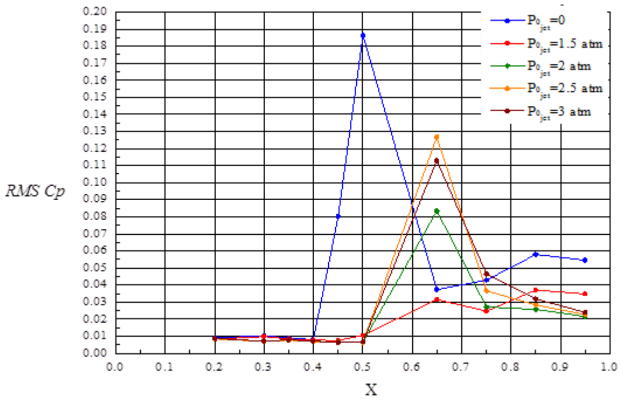


Fig. 11. Root-mean-square values of pressure coefficient pulsations for M=0.76, α=6°.

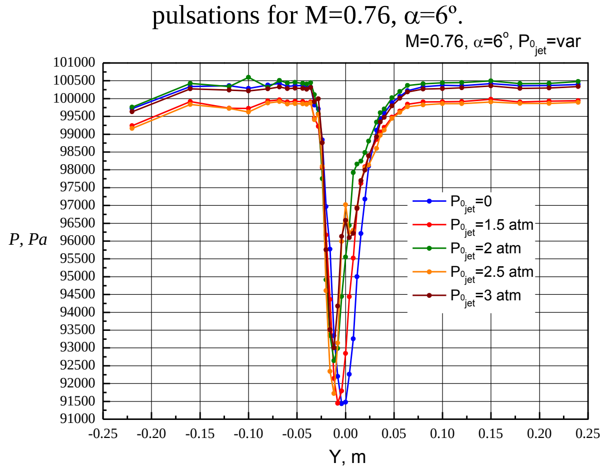


Fig. 12. Total pressure distribution in the wake downstream of the model for M=0.76, α=6°.

Figure 12 shows that the wake is wider for the baseline case without jet blowing. For the cases with jet blowing, the wake is more thin. This trend increases with the increase of jet intensity. It correlates with lift-to-drag ratio increase obtained in numerical simulation.

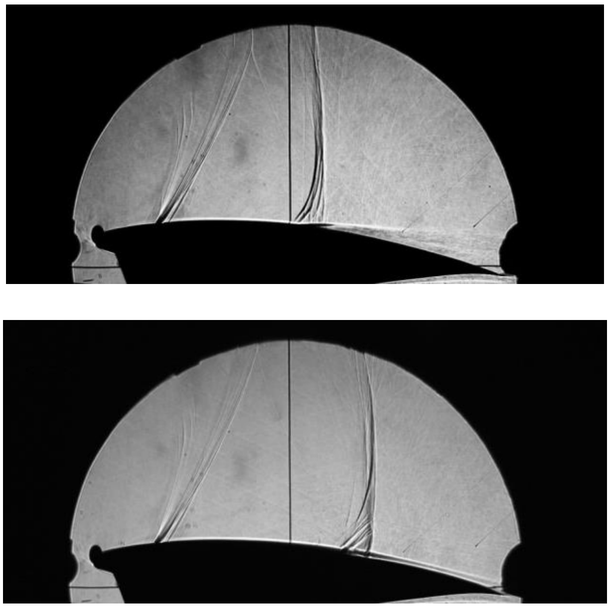


Fig. 13. Shadow images for baseline configuration (upper) and configuration with tangential jet blowing (lower) at P_{0jet}=3 atm; α=6°.

In Fig. 13, one can see the difference between the shock wave positions for the case without blowing (upper image) and for the case with jet blowing (lower one). Moreover, it is clearly seen from the lower image that there is no separation under the shock foot and at the trailing edge for the cases with the jet blowing P_{0jet}=3 atm.

One of the main parameters to be obtained in this experiment was the buffet frequency. The pressure difference in time was obtained using pressure pulsation sensors for each regime. Then the spectra were calculated. Figure 14 shows spectra for the case of α=6° at the section x/c=0.75 and for different Mach numbers. It is clearly seen that there is a discrete peak at ~140 Hz. This peak is relatively close to the value predicted by CFD studies. Two dimensional CFD gives the buffet frequency ~110-120 Hz. In all chordwise sections, there is a second peak approximately at 800 Hz. It should be noted that there is no peak at this frequency on the wall. Probably it can arise on the model due to the three dimensionality of the flow and/or wall interference.

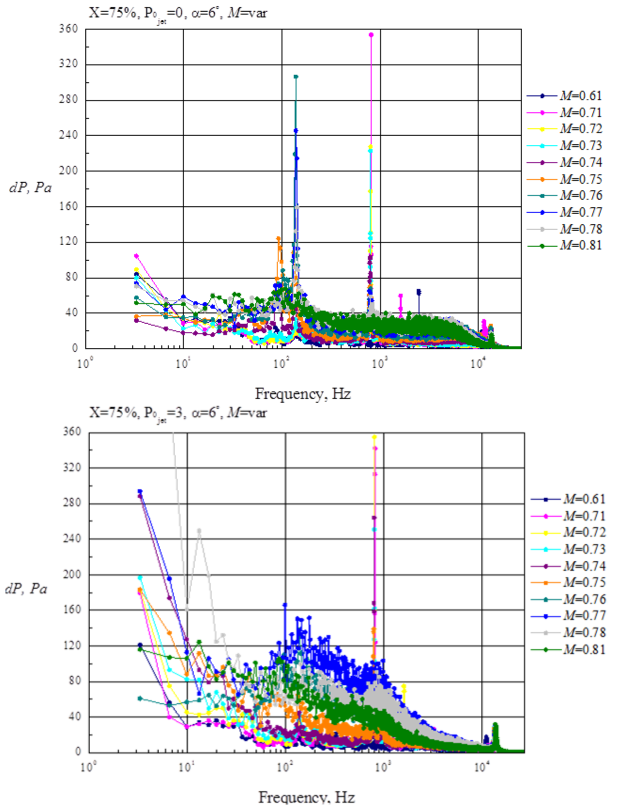


Fig. 14. Spectra of pressure pulsations for α=6° for baseline configuration (upper) and tangential jet blowing (lower) with P_{0jet}=3 atm.

One can see that in the cases with jet blowing, the discrete peak ~140 Hz typical to the baseline configuration disappears while the level of pulsations in this region increases. The peak with ~800 Hz is approximately the same as in the case without jet blowing.

4 Summary

Two-dimensional numerical simulations are carried out to characterize the buffet phenomenon on transonic supercritical airfoil P-184-15SR. Two dimensional CFD gives the buffet frequency ~100-120 Hz. Tangential jet blowing in the shock region is investigated to delay buffet. Numerical simulations showed that the jet suppresses shock-induced separation and increases lift coefficient and lift-to-drag ratio. Numerical results showed that buffet onset delays both in the AoA and C_L domain.

The wind tunnel tests of this configuration with tangential jet blowing were carried out in the TsAGI transonic wind tunnel T-112. The pressure distributions on the airfoil, wind tunnel walls and in the wake have been obtained. Experimental results confirm that the tangential jet blowing moves the shock location downstream at all regimes. The increase of a jet intensity leads to a more downstream location of the shock and a better recovery of the trailing edge pressure. The jet suppresses the shock-induced separation. The buffet frequency was measured as ~140 Hz. This peak is relatively close to the value predicted by CFD studies. In the cases with jet blowing, there is no discrete peak associated with buffet at ~140 Hz.

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