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FLOW STRUCTURE GENERATION BY MULTIPLE JETS IN SUPERSONIC CROSS-FLOW

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ABSTRACT

The flow structure generation by multiple jets impinging a supersonic crossflow in the divergent section of a Convergent-Divergent (C-D) duct is investigated using compressible Large Eddy Simulations (LES). The supersonic flow-field in the C-D duct is mainly characterized by the evolving shock-structure. The effect of increasing the compressible jet to crossflow velocity ratio R to the generation of flow structures and the ability to modify the shock-pattern in the duct was studied. Traversing R , the shock-pattern can be significantly altered. This paper demonstrates that for close located jets in crossflow the vortical structures generated by the jets can interact and give rise to vortical structures in the inter-space plane between the jets. The spectra for different probes are shown illustrating the characteristic flow frequencies. For all simulated cases the spectra show peaks for a defined Strouhal-number of 0.5. The jets choke in the crossflow above an R of about 0.65, which results in a faster disruption of the coherent flow structures induced by the jets. The flow field is analyzed using Proper Orthogonal Decomposition (POD).

1. INTRODUCTION

Jet in crossflow is employed in a vast verity of engineering applications, as e.g. thrust vectoring, fuel injection, mixing processes, and film cooling. Due to the broad field of application, jet in crossflow has been analyzed by many researchers, experimentally and numerically. The focus of research was dedicated to the evolution, stability and the generation mechanisms of the coherent structures [1, 2], the resulted mixing process [3], and the heat transport [4] associated with jet in crossflow.

The governing quantities describing the essential flow phenomena of jet in crossflow are the jet velocity U_j , jet density ρ_j , crossflow velocity U_{cf} , crossflow density ρ_{cf} , the crossflow dynamic viscosity μ_{cf} , the jet dynamic viscosity μ_j , the jet diameter D_j , the boundary-layer thickness or the separation bubble height δ_0^* in front of the jet. Various dimensionless numbers can be constructed using

these variables. However, an important dimensionless parameter that can be defined is the momentum ratio of the jet momentum to the crossflow momentum. For convenience, the quadratic compressible jet to crossflow velocity ratio can be defined as,

$$R^2 = \left(\frac{\rho_j U_j^2}{\rho_{cf} U_{cf}^2} \right). \quad (1)$$

This definition is commonly used to characterize the flow regime of the jet in crossflow. For incompressible flow, R reduces to the velocity ratio of the jet velocity to the crossflow velocity ratio. When the jet media and crossflow media are the same ideal gas and the pressure at the jet orifice is equal the ambient pressure, R simplifies to a Mach-number ratio of the two streams. Other relevant dimensionless numbers are the Reynolds-number Re describing the turbulent flow regime, which can be based on the crossflow quantities U_{cf} , ρ_{cf} , and μ_{cf} or on the jet quantities U_j , ρ_j , D_j , and μ_j . However, in compressible flow also compressibility can play an important role on the evolution of turbulence in the flow.

The dominant characteristic flow structures generated with jet in crossflow are the counter rotating vortex pair, the horse shoe vortex, the jet shear layer, the upright vortices, and the hanging vortices. The counter rotating vortex pair is the most prominent flow structure that spreads with the jet trajectory into the far-field and preserves several jet diameters downstream. The horse shoe vortex is generated at the jet orifice where the crossflow hits the jet. As a smaller flow structure the horse shoe vortex manifests in front of the jet and wraps around the jet. The shear-layer vortices have a ring-like shape and are continuously generated above the horse shoe vortex. These flow structures travel with the flow downstream. Hanging vortices, on the edges of the jet, are caused by a Kelvin-Helmholz instability. These vortical structures are transporting intense velocity fluctuations generated at the jet orifice far along the jet [2].

In sum, there have been performed many studies analyzing a single jet in crossflow. Only a few studies focus on the effect of many jets in crossflow [5] or twin jets in crossflow [6, 7]. This study investigates the flow-

structures evolving due to multiple jets in a supersonic crossflow using compressible LES. The basic geometry used in the simulations is a circular convergent-divergent (C-D) duct. Circumferential disposed jets are used to manipulate the flow pattern, where the aim is to weaken the existing shock-pattern to decrease the losses. Several analyzing methods are used to visualize and identify the flow structures.

2. CASE DESCRIPTION

The behavior of jets exposed to a crossflow in the divergent section of a circular (C-D) confined duct is studied. The jets originate from cylindrical tubes disposed equidistant on the circumference of the duct. Twelve tubes with diameter D_j are inclined 60° to the duct mid-axis and orientated into the duct flow direction. The orifice of the jets is located -0.857 duct exit diameters (D_e) upstream from the duct exit. A visualization of the C-D duct geometry is illustrated in Fig. 1 and the geometric relevant parameters are shown in Tab. 1.

Fig. 1 Showing the geometry of the C-D duct crossflow with the twelve cylindrical tubes disposed in the divergent section.

At the end of the duct, the stream expands into ambient conditions, which are specified in Tab. 1. The operating media is air, obeying the ideal gas law. The isentropic exponent was set to 1.4 and Sutherland's formula was used to account for the temperature dependence of the viscosity, where the standard coefficients were used.

At the inlet of the duct, a total pressures source, four times higher than the ambient pressure p_∞ outside of the duct, is applied. The total temperature $T_{0,n}$ at the inlet is 367° K.

The jets are fed by a compressed air stream originating from ambient conditions without being additionally heated. Thus, the total temperature implied at the jet

inlets $T_{0,i}$ is the ambient temperature T_∞ . The jet flow direction is imposed normal to the jet inlet plane and a total pressure is imposed as driving source.

3. NUMERICAL METHOD

A finite volume code, solving the three-dimensional compressible Navier-Stokes equations, was used for the numerical simulations. Explicit time-stepping using a low-storage four-stage Runge-Kutta scheme was employed for time integration, where the constant time-step Δt was $2.5 \cdot 10^{-8}$ s. A second order central difference scheme was used for spatial discretization. A blend of second and fourth order differences acts as artificial dissipation to suppress numerical solution oscillations near flow discontinuities, as e.g. shocks.

A LES approach was used, where the numerical mesh resolves a substantial range of turbulent energy decay. The small-grid scales terms were not modeled in explicit form. However, the dissipation of the numerical scheme was used to account for the turbulent dissipation.

The entire computational domain includes an inlet section, an investigation section, and a buffer region downstream of the duct section. This buffer region downstream consists of an expansion zone into ambient stagnant conditions, which extends from the duct exit fifteen duct exit diameters downstream, three duct exit diameters upstream, and five duct exit diameters to the side.

A grid stretching is employed towards the domain boundaries in the inlet section and the buffer region downstream to damp reflections at flow inlets and outlets, where characteristic non-reflective boundary conditions were employed. The growth factors are lower than 1.06 in the entire domain.

A fine equidistant cell-spaced section was favored in the investigation section. Adiabatic no-slip boundary conditions were assigned at the nozzle walls. Thus, in the duct region, including injectors, a boundary-layer refined mesh towards the duct walls was utilized. Since, the flow interaction with walls is consequential for the flow structures evolution, modeling the wall boundary with wall functions was abstained.

4. RESULTS

In this section the results of the numerical LES simulations are presented, where the focus of the work is held on the flow-structure development provoked by multiple jets in supersonic crossflow.

4.1 General Flow Observations

Firstly, the general flow-field of the supersonic crossflow shall be described briefly in this section. The baseline is defined as the case without jets streaming into the crossflow, hence $R^2 = 0$. Thus, the pressure in the jet tubes is set to ambient conditions at the jet inlet for this case, which is shown in Fig. 2.

Table 1 Reference values and boundary conditions.

parameter	symbol	value	unit
duct exit diameter	D_e	57.5	mm
injectors diameter	D_j	2.67	mm
area ratio	A_e/A^*	1.23	(-)
duct design Mach-number	$\overline{M}_e$	1.56	(-)
ambient pressure	p_∞	101,325	Pa
ambient temperature	T_∞	288.15	K

Fig. 2 The baseline case, $R^2 = 0$, is presented by instantaneous illustrations of the Mach-number and the density-gradient.

Investigating the flow-field in flow-direction from the left to right, an expansion fan manifests at the narrowest cross-section in the duct, which causes the flow to separate from the duct wall. The formation of a separation bubble and its height is essential for the later observed flow features. At the highest point of the separation bubble a shock-root establishes. The flow reattaches to the nozzle wall at the downstream edge of the injection tube, where a second shock-root forms. The two shock-roots build a lambda shock and merge to an oblique shock. The shock structure amalgamates in the middle of the nozzle to a Mach-disk. At the Mach-disk, a slip-line establishes and the shock is reflected.

The flow, driven by a total pressure source acting at the left inlet, exhibits a laminar flow response. Despite the rather high Reynolds-number of $2.16 \cdot 10^6$, based on the quantities in the narrow cross-section of the duct, the boundary-layer in the nozzle establishes laminar over the entire investigated duct length. However, where the separation bubble hits the injection tube unsteady flow structures are generated.

For low values of $R^2 < 0.15$, the jet creeps on the walls, as it is desired for film cooling of the duct walls. However, the shock-structure can be significantly influenced, compared to baseline. The Mach-disk disappeared and the shock-structure is visibly weakened. For an R^2 of 0.11, the initial formation of a second shock-structure, slightly downstream of the first, which can be seen in Fig. 3(a). Amplifying R^2 to 0.44 the downstream shock-pattern becomes more prominent (see Fig. 3(b)), while the upstream shock-pattern angles become steeper. Furthermore, it can be seen that the jet penetrates into the crossflow and detaches from the duct walls. The downstream shock-pattern becomes the stronger and the structures generated by injection increase significantly for an augmented R^2 to 0.57 (see Fig. 3(c)). When R^2 is intensified in a range of 1.18 to 1.58, a steepening of the upstream shock-pattern has been observed, until the shock-pattern reduces to a bow-shock in front of the jet (see Fig. 3(d)-(f)).

The development of the turbulent kinetic energy distribution as a function of R^2 is shown in Fig. 4 for a close up section around one the jet pipe. At baseline, the shear-layer induced by the flow separation at the narrow

Fig. 3 Evolution of compressible jet to crossflow velocity ratios visualized by the Mach-number contours. (The scale is kept equal for all plots.)

cross-section hits the downstream intersection of the duct walls and the jet-pipe. There, a strong peak of turbulent kinetic energy can be seen, as shown in Fig. 4(a). This peak immediately disappears with a jet flow exhausting the pipe, as shown for the case of $R^2 = 0.11$ in Fig. 4(b). Raising R^2 further to 0.57, the jet detaches from the duct walls and the turbulent kinetic energy distribution shows high levels in the wake of the jet, especially at

Fig. 4 Evolution of turbulent kinetic energy as a function of R for a zoomed in section. (The scale is kept equal for all plots.)

the duct walls, as shown in Fig. 4(c) and (d). Interesting to observe is that the shear-layer, caused by the separation bubble, which incidents the jet shear-layer results a high peak of turbulent kinetic energy levels at this point. The separation bubble increases in size with increased R^2 , as one can observe comparing Fig. 4(c) to (d). The peak value of turbulent kinetic energy appears where the shear-layer interacts with the jet for a R^2 of 0.57, whereas for R^2 above 1.18 the peak value of turbulent kinetic energy emerges at the duct walls in the wake of the jet.

Fig. 5 Illustrating the Görtler-like vortical structures by the λ_2 criteria. Looking from the inlet towards the duct contraction.

The duct geometry exhibits slight rounded transition sections between the straight tube, the convergent section, and the divergent section. Thus, Görtler-like vortices spontaneously arise from the transition of the straight pipe to the convergent section and convect towards the divergent section, as visualized in Fig. 5. The strength of the Görtler-like vortical structures is weaker than the vortical structures in the separation bubble. However, in a spatial small extend the separation bubble is occasionally disrupted by the Görtler-like vortical structures, but not enough to significantly affect the flow-field or the governing flow frequencies downstream. Figure 5 shows an example of a flow-realization in which Görtler-like vortical structures bend over the separation bubble and affect the formation of the vertical structures induced by the injectors. It can also be observed that only a relative small sector of the duct is influenced by a single Görtler-like vortical structure.

4.1.1 Damping Character of the Flow An important flow feature that shall be illustrated, is the damping nature of the compressible flow to the evolution of flow stability in the duct. A case for $R^2 = 1.45$ has been simulated using the inviscid Euler equations, which is shown in Fig.6. Thus, at the duct walls a slip boundary condition was applied. The flow exhibits laminar flow structure in the investigated section and no unsteady flow motion is visible. Even an perturbed initial flow-field converges quickly to a laminarized flow-field. Thus, the unsteadiness of the flow in the viscous case is caused by the vorticity transport, which is generated at the walls.

Fig. 6 The damping character of the flow illustrated by a time-instant showing the Mach-number.

4.1.2 Point Spectral Analysis In several probes the time history of the velocity and pressure signal have been recorded. The power spectra density for the velocity are shown in Fig. 7 for $R^2 = 0.57$ and $R^2 = 1.18$. Three chosen probes are shown, one in the separation bubble close to the narrowest cross-section (orange), another one in the separation bubble close to the jet orifice (red), and one in the shear-layer behind the jet (black), where the locations are indicated in Fig. 2b. The observed frequencies have been made dimensionless, defining a Strouhal-number St using the jet exit diameter d_j and the mean jet velocity $\bar{U}_j$.

A dominant peak frequency in the power spectra density was observed for all investigated R^2 in the shear-layer. Normalized in form of the defined Strouhal-number, a peak in the spectra at an St of 0.5 can be observed for all investigated R^2 . Also the probes located in the separation bubble and in the wake of the jet exhibit this dominant peak. The harmonic of this peak frequency is visible as a hump in the spectra.

For a 90° inclined jet in crossflow, incompressible flow assumption and an R^2 of 0.456 a dominant peak at St of 0.353 was found in [1], which was associated with the hair-pin vortical structures. However, a peak at this St can also be found in the spectra shown in Fig. 7.

The power spectra density of the probes in the separation bubble show further spectral peaks. For an R^2 of 1.18 (shown in Fig. 7), the low frequency oscillating motion of the upstream shock-pattern correlates with the probe in the separation bubble close to the narrows cross-section of the duct.

Although the spectra of all the monitored signals (in

Fig. 7 Power spectra density of the velocity signals observed in the probes (location is indicated with color coded crosses in Fig. 2b).

the separation bubble and the jet wake) exhibit matching spectral peaks, the cross-correlation between the pressure signals in these monitoring points is lower than 0.4. The probes monitoring the Görtler-like vortical structures shows a very low correlation with the other monitoring points in the scope of the jet. The characteristic frequency associated with the Görtler-like vortical structures is more than three orders of magnitude lower than the frequencies associated to the hairpin vortical structures.

4.2 Vortical Structures

The counter rotating vortex pair is the most characteristic flow feature of jets in crossflow and preserves far downstream over the duct length, as one can also observe in Fig. 8. The figure illustrates the formation of the counter rotating vortex pair by (representative positive and negative) iso-surface of axial vorticity component. Clustering of equal spaced segments for each jet can be observed. This deviation into spatial segments acts

Fig. 8 The counter rotating vortex pair is visualized by iso-contours of the axial vorticity, cyan negative and blue positive.

like a symmetry boundary condition. With the separation bubble, prior to the jet streaming into the crossflow, vortical structures generated by the induced shear-layer and shade downstream. However, near in front of the jets, a vortical structure, covering the horse shoe vortex, develops. These structures stretch laterally towards the vortical structures from the other neighboring segment. With the interaction of these vortical structures and the vortical structures shading from the separation bubble, a weaker small counter rotating vortex pair in the interspace plane of the jets is generated. This structure formation can be also clearly seen in Fig. 5.

The vortical hairpin structures have been reported to be very organized for low R [8]. However, at an R^2 higher than 0.65, the jet chokes in this case setup and the formation of a barrel shock at the outlet of the jet leads to a higher frequent vortex shading, as one can see comparing Fig. 9a and Fig. 9b.

Fig. 9 The vortical structures visualized by the λ_2 criteria before the jet chokes (a) and when the jet chokes (b).

4.3 Proper Orthogonal Decomposition

Flow decomposition methods are commonly used to investigate and extract flow features. An overview for the proper orthogonal decomposition method can be found in [9]. Using this method the most energetic flow modes can be visualized. Furthermore, POD has been applied to jet in crossflow, using experimental acquired data [10].

A snapshot approach, using instantaneous velocity data, has been used to compute the modes. 1170 snapshots sampled at a frequency of 266 kHz have been used to compute the modes. The characteristic flow frequencies spread over many orders of magnitudes. Thus, it is hardly possible to capture all occurring frequencies by this approach.

Figure 4 indicates that only a small proportion of the investigated domain in the nozzle exhibits unsteady flow behavior. For the case of $R^2 = 1.18$, the zeroth mode (mean flow) of the POD decomposition carries about 99.5% of the flow energy. Thus, the higher modes representing the unsteady flow motion contain a very low part of the flow energy. The unsteady flow energy distribution for the leading modes of the POD decomposition is shown in Fig. 10a, where fair energy decay over the POD modes can be observed. In Fig. 10b the spectral portrayal of the all computed POD modes is shown, where mainly two peaks can be seen.

For the illustrative chose case of $R^2 = 1.18$, Fig. 11 shows four representative chosen topo modes obtained through the POD decomposition. The leading modes can be associated with the shading of the jet, where the con-

Fig. 10 The distribution of the unsteady flow energy is shown to the left. To the right, the spectra of the chrono modes are plotted, where the modes shown in Fig. 11 are highlighted.

Fig. 11 The topo modes of the POD decomposition are shown.

tours are slightly shifted against each other. However, the peak values occur at different locations. The first two modes are shown in Fig. 11a-b. The corresponding (overlapping) frequencies of the chrono modes are shown in Fig. 10b, where it can be observed that the peak frequencies for the associated chrono modes are around a St of 0.5.

The 3th mode contains the most flow energy with a chrono mode at a low frequency, where the topo mode is shown in Fig. 11c. The shape of the topo mode exhibits a high amplitude at the duct wall in the wake of the jets, which could also be seen in the turbulent kinetic energy levels show in Fig. 4d.

The Görtler-like vortical structures are indicated in the shape of the 12th topo mode, which is shown in Fig. 11d. Furthermore, the shock-structure is visible for this mode. The corresponding chrono mode reveals a frequency at the lower bound of the spectra (see Fig. 10b). However, only a few topo modes contain high magnitudes in the convergent section, where all of them are related to low frequency chrono modes.

5. CONCLUSIONS AND DISCUSSION

Multiple jets disposed at the circumference of a circular C-D duct in a supersonic crossflow have been investigated using compressible LES simulations. Several jet to compressible crossflow velocity ratios have been investigated and the ability to modify the shock-pattern has been shown.

Using inviscid calculations, it could be show that the vorticity is transported from the walls. The influence of the Görtler-like vortical structures generated upstream of the jets on the jet flow-field has been shown to be minor and occurring at a low frequency. The formation of the counter rotation vortex pair and the generation of a secondary counter rotation vortex pair due to the formation of the sections has been shown.

The governing frequencies have been monitored in several probes in the duct. For a defined Strouhal-number, a dominant peak has been observed for all investigated R in the separation bubble in front of the jets and in the downstream section of the jets.

A POD study has been performed and the flow-

structures have been analyzed. 99.5% of the flow energy is comprised by the zeroth mode, since only a small part of the domain exhibits unsteady motion. The dominant peak frequency seen in the probes was confirmed by the POD analysis and the according flow structure has been shown. Also the low frequency flow structures have been identified using the POD decomposition.

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