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2D03 Assessment of URANS and ZDES Simulations for Turbulent Transonic Buffet Predictions on Full-Aircraft Configurations

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Key Words : Turbulent transonic buffet, URANS, hybrid RANS/LES, ZDES, full-aircraft CAT3D

Abstract

Within the context of a bi-lateral joint research collaboration between JAXA and ONERA, unsteady simulations of turbulent transonic buffet are carried out on the ONERA CAT3D full-aircraft configuration. By sharing experimental data and comparing the CFD results independently obtained with the respective in-house CFD codes, both partners aim at validating and assessing the current unsteady CFD methods for buffet prediction. The sensitivities to numerical schemes, turbulence models, grid resolution and temporal integration parameters are analyzed at different levels of fidelity, for both URANS and ZDES calculations. Based on the lessons learnt from this collaborative work, some best-practice recommendations and standing challenges for turbulent transonic buffet prediction are given.

1. Introduction

Transonic buffet is one of the critical unsteady phenomena that limits the flight envelope of an aircraft, occurring for specific combinations of Mach number and the angle of attack. This unsteady phenomenon is an aerodynamic excitation characterized by self-sustained displacements of the shock wave and consequent periodic boundary-layer separation. The correct prediction of this unsteady shock-wave/boundary-layer interaction is a challenging problem for CFD. Moreover, the experimental data that is available for code validation is very limited. Ever since first observed, the scientific community has put great effort to understand the physical mechanism underlying buffet and its onset.

Depending on the configuration, buffet can display a two-dimensional (2D) or three-dimensional (3D) nature. Given their differences, the transonic buffet phenomenon can be divided in two categories: buffet on 2D aerofoils and buffet on 3D airplane wings. While transonic buffet on aerofoils, purely 2D, is nowadays well documented, transonic buffet on wings is not fully understood due to the complexity of its 3D physical mechanisms. For both cases, experimental campaigns and CFD simulations have been carried out to seek a better understanding.

Although the buffet phenomenon on an aerofoil is essentially 2D, Jacquin [1] already noticed that for a

rectangular constant cross section wing 3D weak instabilities were present. As the wing differs from this configuration during buffeting, the 3D effects become dominant. As a result, the buffet over an airplane wing which is often swept, twisted and tapered, displays a 3D nature, showing some differences with respect to its 2D version. As a consequence, transonic buffet on a 3D wing can be much more complex than the periodic chord-wise motions observed on 2D profiles.

Buffet over a wing, as its version over an aerofoil, predominantly consists in a periodic self-sustained motion of the shock, result of an unsteady separated boundary layer. This phenomenon takes place for a given combination of angles of attack and Mach numbers. However, the existence of a separated unsteady boundary layer does not imply the existence of buffet. Contrary to 2D buffet, the motion of the shock does not correspond with an isolated peak in the spectrum but with broadband bumps at Strouhal numbers 4 and 7 times higher [2, 3, 4]. As the analysis of the experimental data performed by Dandois shows [4], these Strouhal numbers are within the range $0.2 < St < 0.6$. In addition to this phenomenon, Kelvin-Helmholtz instability, also present in the 2D buffet [5], ranging between $1 < St < 4$ are also found on the suction side of the wing. Another characteristic of the swept wing buffet is that the shock unsteadiness often first emerges at the wingtip and progresses inboard with increasing angle of attack.

An explanation for the differences arising between the 2D and 3D buffet phenomena can be attributed by a span-wise propagation of the so called “buffet cells” introduced by Iovnovich and Raveh [6]. Experiments on the CRM by Koike et al. [7] found that these span-wise undulations are originated near the wing root and propagated outboard towards the tip, at a convection speed that decreases with an increase in angle of attack. These motions have been the subject of numerous studies in recent years. Crouch [8] and Paladini [9] were able to link the presence of these motions to the superposition of two global instabilities. Moreover, the convection of those cells towards the wing tip has been related to the wing sweep angle.

Numerous numerical studies seeking the correct prediction of the 3D buffet by means of CFD have been carried out in the past decades. Being the least computational costly, RANS has been able to successfully predict buffet onset [10]. Nonetheless, due to its steady nature, no unsteady information on the buffet itself can be obtained. Sartor and Timme [11] used a URANS approach to reproduce the dominant flow features. This was feasible since shock motions occur at time scales that are much longer than those of the wall-bounded turbulence. However, the result is strongly dependent on the turbulent model and the angle of attack has to be increased with respect to the experimental one. Moreover, different authors [12, 13] pointed out that scale-resolving methods provide a better agreement with experimental data. For instance, DDES and ZDES are capable of capturing a rich turbulent spectrum of the structures being shed away from the foot shock and DDES yields the right curvature of the outboard mean shock foot trace.

Because of the questions that still remain unanswered in the domain of buffet simulation, ONERA and JAXA decided to share experimental results of transonic buffet and compare CFD results against the data, in order to validate the CFD codes and assess the current unsteady methods for the buffet prediction. Two test cases are planned in the joint research: this manuscript resumes the results of the ONERA test case, the “CAT3D model”. The geometries and the experimental data of the CAT3D model have been provided by ONERA. The parties simulated the transonic buffet using their own in-house codes (*elsa* for ONERA [14] and *FaSTAR* for JAXA [15])

and then shared the results using different techniques.

This manuscript proceeds as follow: after a brief presentation of the well-known CAT3D model and the experimental data shared in this collaboration, each partner presents a summary of their work in separate sections. Then, results are compared with each other and validated against the experimental data. The lessons learnt by the partners as well as the best-practices for future simulations are summarized in the conclusions.

2. The Test Case: ONERA CAT3D Model

All the calculations will be conducted on the same geometry, which was created for the purposes of the EU-funded AVERT “Aerodynamic Validation of Emission Reducing Technologies” project launched in 2007 and coordinated by Airbus Operations Ltd. The AVERT model was named CAT3D and consists in a half-model geometry composed of a wing and fuselage.

The geometry is depicted in Figure 1: the wing section is based on the OAT15A supercritical profile which has a thickness to chord ratio of 12.5% and a thick trailing edge of 0.5% of the chord length. The wing span of the CAT3D model is 1.225m and the wing sweep angle is 30°. The mean aerodynamic chord is 0.3375m with a maximum value of 0.450m at the wing root and a minimal value of 0.225m at the wing tip. The wing twist was adapted so that the shock would remain parallel to the leading edge. The database used for validation of the simulations presented in this work corresponds to the experimental campaign performed in ONERA S2MA wind tunnel, result of the EU-funded AVERT project. Only a part of this database is shared between ONERA and JAXA for validating the results.



Figure 1: CAT3D model at ONERA S2MA wind tunnel.

The experimental campaign was conducted in the ONERA S2MA wind tunnel, a continuous pressurized subsonic, transonic and supersonic wind tunnel. Its test section of 1.75 m by 1.77 m, allows the use of relatively large models, such as the CAT3D. So as to study the transonic buffet, the model was equipped with 86 steady pressure taps distributed over 4 wing sections, 65 on the upper surface and 21 on the lower surface of the wing. Additionally, 57 unsteady transducers spread over 7 wing sections, 53 on the upper surface and 4 on the lower surface of the wing were included. Additionally, 6 accelerometers on 3 wing sections, 2 per wing section, were installed.

The test conditions are presented in Table 1. Both partners used the same boundaries conditions for their simulations: non reflective condition on the far-field and adiabatic walls on the model surface.

Case	Mach	AoA (α)	Reynolds
Steady	0.826	2.54°	2.84×10^6
Unsteady	0.826	4.22°	2.84×10^6

Table 1: Test conditions for the two considered points

A structured multi-block grid was also shared between partners. This grid has been used by ONERA for the RANS and URANS simulations. JAXA, who has an unstructured solver, used this grid as a reference for creating their mesh. The computational domain is a multi-blocks H-type structured grid composed of 327 blocks and the mesh is composed of approximately 5.2 M points. A refined grid has then been created by both partners for the ZDES simulations.

3. Summary of the Numerical Results

In the next subsections, a summary of the results independently obtained by ONERA and JAXA are discussed. For the sake of conciseness, these summaries only report the main observations.

3.1. Results of ONERA

Steady-state simulations were first considered for investigating transonic buffet. In the low incidence case, where no unsteady phenomena are expected, convergence was achieved and simulations were consistent with

experiments: RANS simulations successfully captured the physics of the flow. However, in the high incidence case, where large separation may occur, calculations did not converge and an important separated area was predicted by steady-state simulations. These observations encouraged to perform time-accurate calculations in the high incidence case. The influence of various numerical parameters was assessed, and it was concluded that the major parameter that affects the solution is the choice of the turbulence model. The effects of laminar to turbulent transition and wing deformation were also investigated. It was shown that they do have a limited influence on the final results. For the baseline grid, URANS has proved to be able to reproduce the transonic buffet within the limitations of modelled turbulence. In other words, it was solely capable of reproducing the flow characteristics associated with time scales larger than the ones associated with turbulence. However, since shock motions are low-frequency, it managed to reproduce the periodic shock oscillation at a Strouhal number of 0.22. The overall flow field was in satisfying agreement with the experimental data.

ZDES was then considered and a simulation was run on a chimera box type grid (figure 2) producing a total of 6 transonic buffet cycles. Prior to this final simulation, diverse combinations of schemes and grid split were tried. From this study, it was found that third-order limiter and AUSM+P MiLES was unstable for the refined grid.

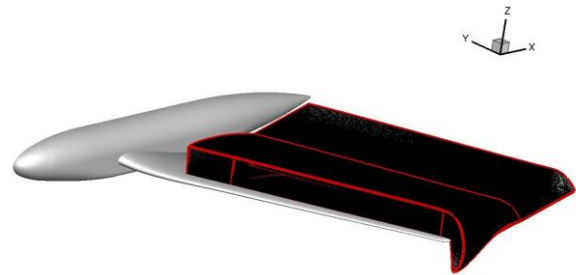


Figure 2: Chimera box containing the refined grid for the ZDES simulation.

From the ZDES simulation it can be concluded that its protection function behaves as expected, correctly securing the boundary layer and allowing the development of instabilities. Additionally, the grey area between RANS and LES is narrow, prompting a fast switch from one model to the other. With regards to the reproduction of the flow field, it was noted that there is an overestimation of the levels of turbulence after the shock.

This leads to a prediction of the shock too upstream for those span-wise locations where these fluctuations are most intense. A reason for this could be due to the combination of a dissipative scheme and coarse grid. It has been found previous studies at ONERA that coarse grids in the normal direction led to an intensification of the fluctuations downstream the shock. Consequently, it would be interesting to generate a more robust grid, refined in the normal direction that could allow the use of less dissipative AUSM+P MiLES scheme. Lastly, the simulation should be run for a longer period of time, yielding at least 10 buffet cycles. Nonetheless, within the limitations of this preliminary simulation both in terms of grid and computational time, ZDES was able to reproduce the transonic buffet. It yielded a frequency spectrum with two dominant peaks within the expected Strouhal number range and it captures features such as the buffet cells. It also provided detailed information about the shape and size of the eddies shed downstream the foot shock.

3. 2. Results of JAXA

The experiments carried out at ONERA S2MA wind tunnel on the CAT3D half wing-body configuration are numerically investigated using RANS, URANS and ZDES approaches and several sensitivity studies are performed. For the low angle of attack of $AoA=2.54^\circ$, the steady flow is generally well predicted by RANS simulations and very good agreement is obtained with Brunet and Deck [16] RANS results. The unsteady flow features at $AoA=4.22^\circ$ are analysed with URANS calculations. Despite the prediction of small fluctuations along the shock wave, the overall agreement with the experiments is not satisfactory. ZDES simulations at $AoA=4.22^\circ$ are carried out using different definitions of the RANS region height distribution in the wing span-wise direction. A precise prediction of the shock location is proved difficult also due to the presence of unphysical pressure fluctuations in the inboard region at $y/b=30\%$. While the use of the QCR method does not significantly change the results, the restriction of the ZDES approach (figure 3) in the middle and outboard wing and wake regions improves the agreement with the experiments and ZDES results by Brunet and Deck [16]. However, some differences still exist. A closer match with the ZDES results by Brunet and Deck [16] is obtained when a finer grid is considered but the shock location is still predicted farther upstream with respect to the experimental data.

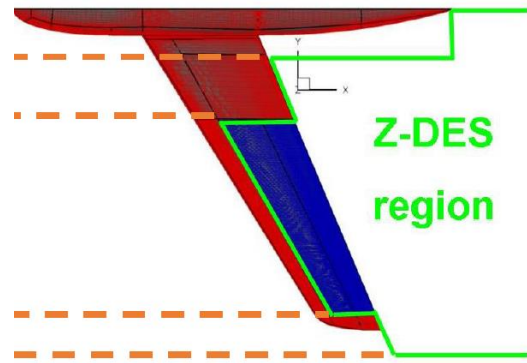


Figure 3: Definition of the ZDES and RANS regions adopted for the present simulations based on visual inspection of the figure by Brunet and Deck [16].

4. Comparisons

This section presents a comparison between ONERA and JAXA results versus the experimental data, when available. While for the steady case at $AoA=2.54^\circ$ only the RANS results are compared, for the unsteady case at $AoA=4.22^\circ$ both URANS and ZDES are considered.

4. 1. RANS: Steady case at $AoA=2.54^\circ$

In this section, ONERA's results correspond to the SA turbulence model with AUSM+P scheme, without wing deformation. Similarly, JAXA's results correspond to the SA turbulence model with HLLW scheme. The same grid was used by both institutions: the reference grid shared at the beginning of the collaboration. The RANS C_p profiles at different span-wise locations are plotted in Figure 4. A remarkable good agreement between the simulations and the experiments can be seen except in the vicinity of the body-wing junction, being a notoriously difficult region to be well predicted by RANS simulations. The C_p contours on both fuselage and wing are reported in Figure 5 for the RANS results obtained by ONERA (left half) and JAXA (right half) and the agreement between the numerical results is confirmed on the whole model. Despite the sensitivity of the solution on the modelling of turbulence (not shown here), when the same turbulence model (it should be noted that the implementations of the SA model by ONERA and JAXA are not exactly the same) is used on the same grid, the CFD results of the two institutions are in excellent agreement with each other and with respect to the experiments. This section shows the capability and reliability of RANS simulations to accurately capture the flow features of the CAT3D model at steady conditions.

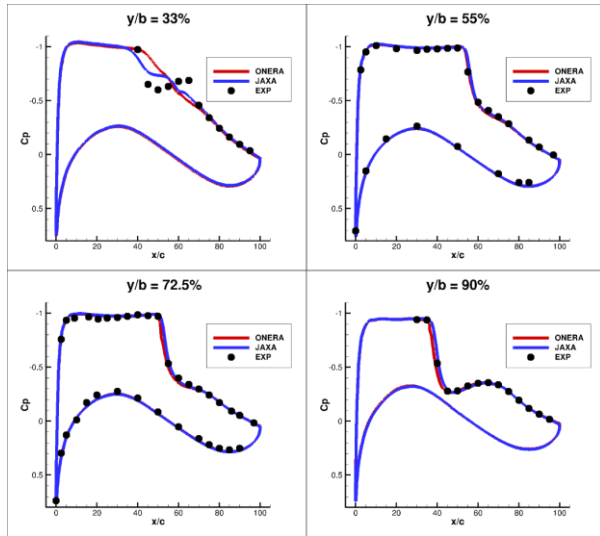


Figure 4: RANS C_p distributions by ONERA (red line) and JAXA (blue line) for the $AoA=2.54deg$ at different span-wise stations. The experimental results are indicated by the circles.

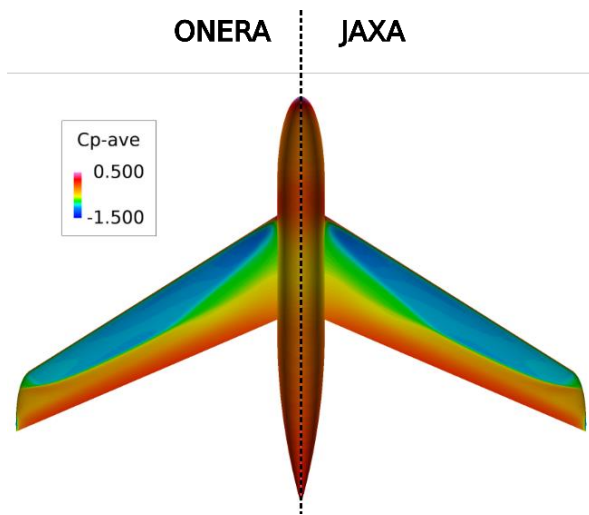


Figure 5: RANS C_p surfaces at $AoA=2.54deg$ obtained by ONERA (left half) and JAXA (right half).

4. 2. URANS: Unsteady case at $AoA=4.22^\circ$

The $AoA=4.22^\circ$ was experimentally found to be an unsteady case due to the occurrence of the buffet phenomenon. For this reason, the RANS investigations at this AoA failed to reproduce the flow features and URANS time-accurate simulations were carried out. In this section, both ONERA's and JAXA's results correspond to the same turbulence model, spatial scheme, and wing deformation of the previous section. As for the steady-state simulations, the same grid was used by both institutions. The URANS time-averaged C_p profiles at

different span-wise locations are plotted in Figure 6. While a reasonable agreement between CFD and experiments exists, the difficulty of the numerical simulations to accurately capture the mean location of the shock wave is evident. Despite ONERA's results seem to perform better at certain span-wise locations, the CFD shock positions are generally predicted farther downstream with respect to the experiments.

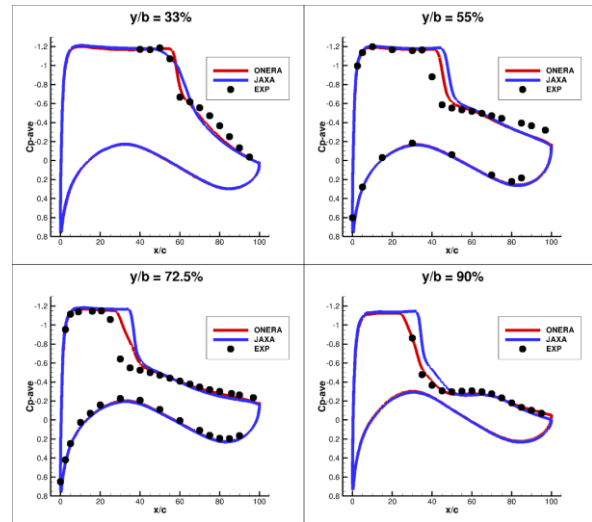


Figure 6: URANS time-averaged C_p distributions by ONERA (red line) and JAXA (blue line) at different span-wise stations. The experimental results are indicated by the circles.

To better quantify the unsteady character of the flow, the URANS dimensional pressure RMS are compared with the experimental ones in Figure 7. The pressure fluctuations confirm the CFD shocks to appear downstream of the experimental ones and show a quantitative underprediction of the unsteady flow features. The differences between CFD and experimental data might be caused by the limitations of the URANS modelling approach in capturing small turbulent scales. While the agreement between the CFD results can be considered to be reasonably good in a time-averaged sense, the fluctuations predicted by JAXA are weaker than those obtained by ONERA. The causes of these discrepancies might be due to two main factors: first, different parameters for the time-integration were used (12 and 5 inner iterations use by ONERA and JAXA, respectively), second, while JAXA uses the same spatial scheme to compute mean and turbulent numerical fluxes, ONERA can independently apply different ones. These aspects will be the focus of future investigations.

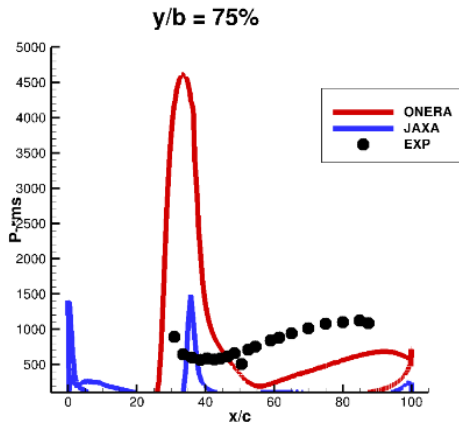


Figure 7: URANS dimensional pressure RMS distributions (in Pascals) by ONERA (red line) and JAXA (blue line) for the $AoA=4.22deg$ at $y/b=75.0\%$. The experimental results are indicated by the circles.

4. 3. ZDES: Unsteady case at $AoA=4.22^\circ$

The time-accurate URANS simulations showed some differences with respect to the experiments that are intended to be eliminated by resolving the small turbulent scale unsteady dynamics in the separated region with the ZDES approach. ONERA's results are those obtained on a grid that is composed by the baseline grid used for the RANS/URANS simulation superposed to a fine grid with Chimera technique (figure 2), while JAXA's ones correspond to the fine grid calculations obtained on a modified grid based on the provided one. It should be noted that, besides the differences in the choice of the time-integration parameters and applied spatial schemes for the calculation of the numerical fluxes mentioned in the URANS comparison section, the numerical setups by ONERA and JAXA differ on several other aspects. Firstly, different grids with different resolutions (about 93.5 million and 42.7 million for ONERA and JAXA, respectively) were used, with ONERA having a very fine zone in the buffet region only, and JAXA preferring to use a more uniform solution, proportional to the reference grid. Then, the definition of the RANS region (within the ZDES approach) is done automatically by ONERA by using the so-called Mode-2 ZDES, allowing for a user-free switch between RANS and LES MODE, while it is for JAXA decided by a preliminary calculation.

Similarly to what done for the URANS comparisons, the ZDES time-averaged C_p profiles and the dimensional pressure RMS at several span-wise locations are compared with the experiments in Figures 8 and 9,

respectively. As a general remark for both CFD data by ONERA and JAXA, the shock wave moves upstream with respect to the URANS calculations. Despite the CFD shock location of ONERA's results seems to get closer to the experiments, significant differences still exist downstream of the shock in the separated region. For JAXA's results, the shock moves too far upstream in the wing root region, with a consequent inaccurate prediction all the way towards the wing tip. For both ONERA and JAXA, the ZDES pressure RMS now overestimates the experimental values, suggesting that the numerical grids used might not be fine enough.

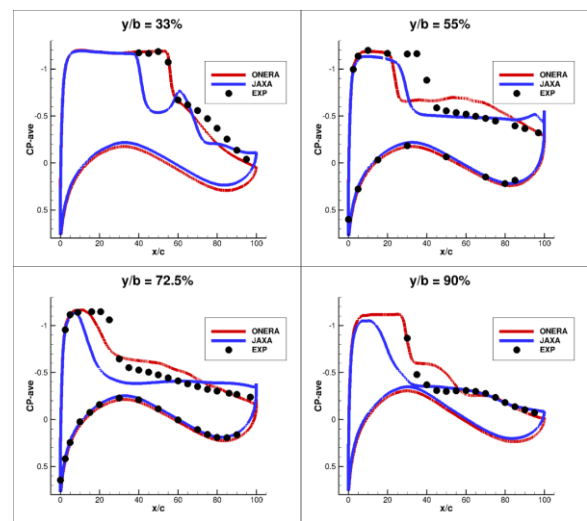


Figure 8: ZDES time-averaged C_p distributions by ONERA (red solid line) and JAXA (blue solid line) for the $AoA=4.22deg$ at different span-wise stations. The experimental results by the circles.

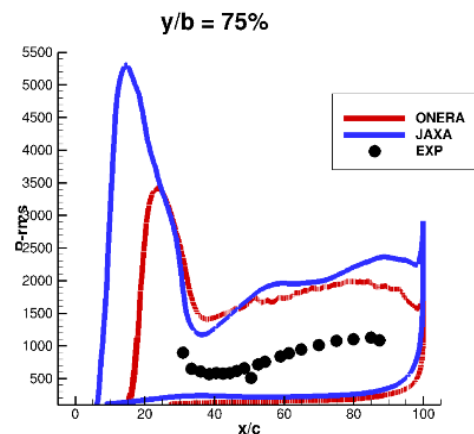


Figure 9: ZDES dimensional pressure RMS distributions (in Pascals) by ONERA (red solid line) and JAXA (blue solid line) for the $AoA=4.22deg$ at $y/b=75.0\%$. The experimental results by ONERA are indicated by the circle symbols.

The CFD lift coefficients-based PSD distributions are shown in Figure 10 along with the experimental local pressure spectra at several span-wise locations (being the spectra done on different quantities, the CFD lift coefficient PSD were arbitrarily rescaled by the same amplitude to visually match the experimental ones).

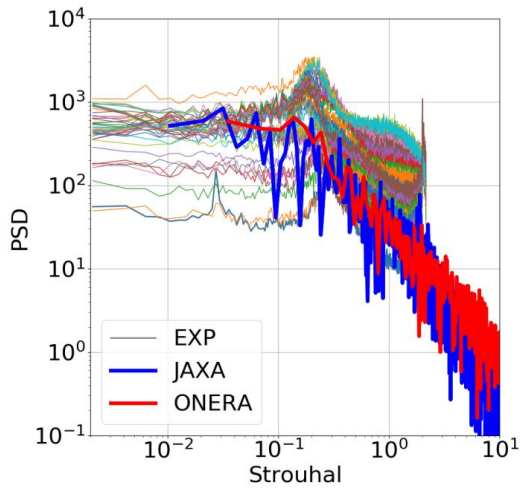


Figure 10: CFD lift coefficient PSD for ONERA (thick red line) and JAXA (thick blue line). The thin colored solid lines correspond to the experimental data.

Both numerical PSD distributions from ONERA and JAXA indicate a high energy content in the low-frequency range (i.e. around $St=0.2$) characteristic of the 3D periodic motion of transonic buffet, compatibly with the experiments. Longer signals are needed to better reproduce the low-frequency energy content of the experiments, but overall spectral agreement exists between the CFD simulations. While the spectral energy content of the CFD simulations obtained by ONERA and JAXA is similar, significant differences exist in the dimensional pressure RMS contours on both fuselage and wing reported in Figure 11. The aforementioned numerical setup choices clearly have a severe impact on the numerical predictions and offer opportunities for the improvement of the investigations and codes.

5. Conclusions and Lessons Learnt

The comparison between partners' results and the experimental data allows drawing some important conclusions about the limitation of the approach in general, or the limitation of each CFD codes. Concerning ONERA results, RANS and URANS simulation proved that, despite the limitations of the approach, mid-fidelity

simulations are capable of reproducing transonic buffet and thus present a strong interest for industrial research. The comparison between different models and numerical schemes showed that the medialisation of turbulence and the discretisation of the fluxes still present a central role in the buffet simulation. However, the lack of small-scale resolution indicates that a high-fidelity approach is needed when in search for a deeper analysis of the phenomenon.

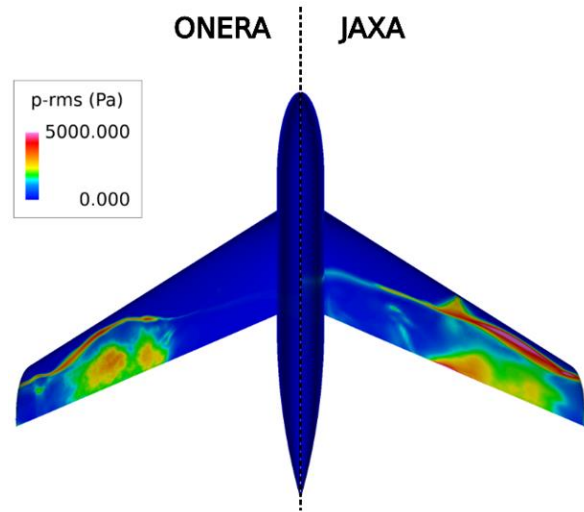


Figure 11: ZDES dimensional pressure RMS surfaces at $AoA=4.22deg$ obtained by ONERA (left half) and JAXA (right half).

With this respect ZDES has proven to be well adapted for an accurate description of transonic buffet. However, this technique requires the use of a very fine grid and ONERA results indicate that the results could be improved by an even finer grid, especially if it allows for the use of a less dissipative scheme. Finally, the physical duration of the simulation should be increased for a more accurate representation of the periodic motions, which requires more data to feed the statistics: ONERA underestimates the CPU cost of the simulation and was not able to provide a longer signal.

Concerning JAXA results, it has been shown that RANS and URANS are capable of reproducing the phenomenon, but a high-fidelity approach is required. Some differences with respect to ONERA's approach indicate sensitivity to time-integration parameters and flux discretization schemes that need to be taken into account for future investigations. The grid-dependency analysis on the ZDES results showed also the importance of the mesh density, which should not be underestimated for

scale-resolving simulations. The definition of the RANS region within the ZDES approach also showed large effects on the description of the buffet dynamics and a preferred/suggested solution remains to be provided.

Overall, the lesson learnt thanks to those simulations will allow for a better simulation of the CRM model, which will be the test-case for the next work package of the collaboration between ONERA and JAXA.

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