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Global instability of wing shock-buffet onset. (English) Zbl 07154371

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Summary: Shock buffet on wings encountered in edge-of-the-envelope transonic flight remains an unresolved and disputed flow phenomenon, challenging both fundamental fluid mechanics and applied aircraft aerodynamics. Its dynamics is revealed through the interaction of spanwise shock-wave oscillations and intermittent turbulent boundary-layer separation. Resulting unsteady aerodynamic loads, and their mutual working with the flexible aircraft structure, need to be accounted for in establishing the safe flight envelope. The question of global instability leading to this flow unsteadiness is addressed herein. It is shown for the first time on an industrially relevant configuration that the dynamics of a single unstable oscillatory eigenmode plays a prominent role in near-onset shock buffet on a quasi-rigid wing. Its three-dimensional spatial structure, previously inferred both from experiment and time-marching simulation, describes a spanwise-localised pocket of shear-layer pulsation synchronised with an outboard-propagating shock oscillation. The results also suggest that the concept of a critical global shock-buffet mode commonly reported for two-dimensional aerofoils also applies to three-dimensional finite and swept wings, albeit different modes at play. Specifically, the modern wing design, NASA Common Research Model, with publicly available geometry and experimental data for code validation is studied at a free-stream Mach number of 0.85 with Reynolds number per reference chord of 5.0×10^6 and varying angle of attack between 3.5° and 4.0° targeting the instability onset. Strouhal number at instability onset just above 3.7° is approximately 0.39. At the same time, a band of eigenmodes shows reduced decay rate in the Strouhal-number range of 0.3 to 0.7, with additional unstable oscillatory modes appearing beyond onset. Importantly, those emerging modes seem to discretise the continuous band of medium-wavelength modes, as recently reported for infinite swept wings using stability analysis, hence generalising those findings to finite wings. Through conventional time-marching unsteady simulation it is explored how the critical linear eigenmode feeds into the nonlinearly saturated limit-cycle oscillation near instability onset. The established numerical strategy, using an iterative inner-outer Krylov approach with shift-and-invert spectral transformation and sparse iterative linear solver, to solve the arising large-scale eigenvalue problem with an industrial Reynolds-averaged Navier-Stokes flow solver means that such a practical non-canonical test case at a high-Reynolds-number condition can be investigated. The numerical findings can potentially be exploited for more effective unsteady flow analysis in future wing design and inform routes to flow control and model reduction.

MSC:

76 Fluid mechanics

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absolute/convective instability; computational methods; high-speed flow

Software:

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References:

[1] Allmaras, S. R., Johnson, F. T. \& Spalart, P. R.2012Modifications and clarifications for the implementation of the Spalart-Allmaras turbulence model. In ICCFD7-1902, 7th International Conference on Computational Fluid Dynamics, Big Island, Hawaii, 9-13 July 2012. ICCFD.

[2] Barkley, D.2006Linear analysis of the cylinder wake mean flow. Europhys. Lett.75 (5), 750-756.

[3] Barkley, D., Blackburn, H. M. \& Sherwin, S. J.2008Direct optimal growth analysis for timesteppers. Intl J. Numer. Meth. Fluids57 (9), 1435-1458. · Zbl 1144.76044

[4] Belesiotis-Kataras, P. \& Timme, S.2018Numerical study of incipient transonic shock buffet on large civil aircraft wings. In

Royal Aeronautical Society 2018 Applied Aerodynamics Conference.

[5] Brion, V., Dandois, J., Abart, J.-C. \& Paillart, P.2017Experimental analysis of the shock dynamics on a transonic laminar airfoil. EUCASS Prog. Flight Phys.9, 365-386.

[6] Brunet, V. \& Deck, S.2008Zonal-detached eddy simulation of transonic buffet on a civil aircraft type configuration. In 38th Fluid Dynamics Conference and Exhibit, Fluid Dynamics and Co-located Conferences, AIAA Paper 2008-4152.

[7] Burroughs, E. A., Romero, L. A., Lehoucq, R. B. \& Salinger, A. G.2001 Large scale eigenvalue calculations for computing the stability of buoyancy driven flows. Tech. Rep. Sandia National Laboratories.

[8] Crouch, J. D., Garbaruk, A. \& Magidov, D.2007Predicting the onset of flow unsteadiness based on global instability. J. Comput. Phys.224 (2), 924-940. · Zbl 1123.76018

[9] Crouch, J. D., Garbaruk, A., Magidov, D. \& Travin, A.2009Origin of transonic buffet on aerofoils. J. Fluid Mech.628, 357-369. · Zbl 1181.76092

[10] Crouch, J. D., Garbaruk, A. \& Strelet, M.2019Global instability in the onset of transonic-wing buffet. J. Fluid Mech.881, 3-22. · Zbl 1430.76343

[11] Dandois, J.2016Experimental study of transonic buffet phenomenon on a 3D swept wing. Phys. Fluids28 (1), 016101.

[12] Dandois, J., Mary, I. \& Brion, V.2018Large-eddy simulation of laminar transonic buffet. J. Fluid Mech.850, 156-178. · Zbl 1415.76396

[13] Deck, S.2005Numerical simulation of transonic buffet over a supercritical airfoil. AIAA J.43 (7), 1556-1566.

[14] Dor, J. B., Mignosi, A., Seraudie, A. \& Benoit, B.1989Wind tunnel studies of natural shock wave separation instabilities for transonic airfoil tests. In Symposium Transsonicum III. International Union of Theoretical and Applied Mechanics, pp. 417-427. Springer.

[15] Dwight, R.2006 An implicit LU-SGS scheme for finite-volume discretizations of the Navier-Stokes equations on hybrid grids Tech. Rep. DLR-FB-2005-05. German Aerospace Center.

[16] Elman, H. C., Meerbergen, K., Spence, A. \& Wu, M.2012Lyapunov inverse iteration for identifying Hopf bifurcations in models of incompressible flow. SIAM J. Sci. Comput.34 (3), A1584-A1606. · Zbl 1247.65047

[17] Eriksson, L. E. \& Rizzi, A.1985Computer-aided analysis of the convergence to steady state of discrete approximations to the Euler equations. J. Comput. Phys.57 (1), 90-128. · Zbl 0624.76078

[18] Feldhusen-Hoffmann, A., Statnikov, V., Michael, K. \& Schröder, W.2018Investigation of shock-acoustic-wave interaction in transonic flow. Exp. Fluids59 (1), 15.

[19] Giannelis, N. F., Vio, G. A. \& Levinski, O.2017A review of recent developments in the understanding of transonic shock buffet. Prog. Aerosp. Sci.92, 39-84.

[20] Grossi, F., Braza, M. \& Hoarau, Y.2014Prediction of transonic buffet by delayed detached-eddy simulation. AIAA J.52 (10), 2300-2312.

[21] Hartmann, A., Feldhusen, A. \& Schröder, W.2013On the interaction of shock waves and sound waves in transonic buffet flow. Phys. Fluids25 (2), 026101.

[22] He, W., Tendero, J. A., Paredes, P. \& Theofilis, V.2017Linear instability in the wake of an elliptic wing. Theor. Comput. Fluid Dyn.31, 483-504.

[23] He, W. \& Timme, S.2020Triglobal shock buffet instability study on infinite wings. In AIAA SciTech 2020 Forum, AIAA Paper 2020-1986.

[24] Hefer, G.2003ETW - A facility for high Reynolds number testing. In IUTAM Symposium Transsonicum IV (ed. Sobieczky, H.), pp. 157-164. Springer.

[25] Iorio, M. C., Gonzalez, L. M. \& Ferrer, E.2014Direct and adjoint global stability analysis of turbulent transonic flows over a NACA0012 profile. Intl J. Numer. Meth. Fluids76 (3), 147-168.

[26] Iovnovich, M. \& Raveh, D. E.2015Numerical study of shock buffet on three-dimensional wings. AIAA J.53 (2), 449-463.

[27] Jacquin, L., Molton, P., Deck, S., Maury, B. \& Soulevant, D.2009Experimental study of shock oscillation over a transonic supercritical profile. AIAA J.47 (9), 1985-1994.

[28] Keye, S. \& Gammon, M. R.2018Development of deformed computer-aided design geometries for the Sixth drag prediction workshop. J. Aircraft55 (4), 1401-1405.

[29] Koike, S., Ueno, M., Nakakita, K. \& Hashimoto, A.2016Unsteady pressure measurement of transonic buffet on NASA Common Research Model. In 34th AIAA Applied Aerodynamics Conference, AIAA Aviation 2016 Forum, AIAA Paper 2016-4044.

[30] Kroll, N., Langer, S. \& Schwöppe, A.2014The DLR flow solver TAU - status and recent algorithmic developments. In 52nd Aerospace Sciences Meeting, AIAA Paper 2014-0080.

[31] Langer, S.2014Agglomeration multigrid methods with implicit Runge-Kutta smoothers applied to aerodynamic simulations on unstructured grids. J. Comput. Phys.277, 72-100. · Zbl 1349.76353

[32] Lawson, S., Greenwell, D. \& Quinn, M. K.2016Characterisation of buffet on a civil aircraft wing. In 54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, AIAA Paper 2016-1309.

[33] Lee, B. H. K.1990Oscillatory shock motion caused by transonic shock boundary-layer interaction. AIAA J.28 (5), 942-944.

[34] Lehoucq, R., Sorensen, D. \& Yang, C.1998ARPACK Users' Guide. SIAM.

[35] Lutz, T., Gansel, P. P., Waldmann, A., Zimmermann, D.-M. \& Schulte am Hülse, S.2016Prediction and measurement of the

Common Research Model wake at stall conditions. J. Aircraft53 (2), 501-514.

[36] Mack, C. J. \& Schmid, P. J.2010A preconditioned Krylov technique for global hydrodynamic stability analysis of large-scale compressible flows. J. Comput. Phys.229 (3), 541-560. · Zbl 1253.76042

[37] Martineau, D. G., Stokes, S., Munday, S. J., Jackson, A. P., Gribben, B. J. \& Verhoeven, N.2006Anisotropic hybrid mesh generation for industrial RANS applications. In 44th AIAA Aerospace Sciences Meeting and Exhibit, AIAA Paper 2006-534.

[38] Maschhoff, K. J. \& Sorensen, D. C.1996P_ARPACK: an efficient portable large scale eigenvalue package for distributed memory parallel architectures. In Applied Parallel Computing Industrial Computation and Optimization, PARA 1996, , vol. 1184. Springer. · Zbl 0886.65034

[39] Masini, L., Timme, S., Ciarella, A. \& Peace, A.2017Influence of vane vortex generators on transonic wing buffet: further analysis of the BUCOLIC experimental dataset. In Proceedings of the 52nd 3AF International Conference on Applied Aerodynamics, Lyon, France (2017). 3AF.

[40] Masini, L., Timme, S. \& Peace, A. J.2018Scale-resolving simulation of shock buffet onset physics on a civil aircraft wing. In Royal Aeronautical Society 2018 Applied Aerodynamics Conference. Royal Aeronautical Society. · Zbl 07150040

[41] Masini, L., Timme, S. \& Peace, A. J.2019Reynolds number effects on wing shock buffet unsteadiness. In AIAA Aviation 2019 Forum, AIAA Paper 2019-2820. · Zbl 07150040

[42] Masini, L., Timme, S. \& Peace, A. J.2020Analysis of a civil aircraft wing transonic shock buffet experiment. J. Fluid Mech.884, A1. · Zbl 07150040

[43] McCracken, A., Da Ronch, A., Timme, S. \& Badcock, K. J.2013Solution of linear systems in Fourier-based methods for aircraft applications. Intl J. Comput. Fluid Dyn.27 (2), 79-87.

[44] Merienne, M.-C., Le Sant, Y., Lebrun, F., Deleglise, B. \& Sonnet, D.2013Transonic buffeting investigation using unsteady pressure-sensitive paint in a large wind tunnel. In 51st AIAA Aerospace Sciences Meeting, AIAA Paper 2013-1136.

[45] Mettot, C., Sipp, D. \& Bézard, H.2014Quasi-laminar stability and sensitivity analyses for turbulent flows: prediction of low-frequency unsteadiness and passive control. Phys. Fluids26, 045112.

[46] Ohmichi, Y., Ishida, T. \& Hashimoto, A.2018Modal decomposition analysis of three-dimensional transonic buffet phenomenon on a swept wing. AIAA J.56 (10), 3938-3950.

[47] Paladini, E., Beneddine, S., Dandois, J., Sipp, D. \& Robinet, J.-C.2019aTransonic buffet instability: from two-dimensional airfoils to three-dimensional swept wings. Phys. Rev. Fluids4, 103906.

[48] Paladini, E., Dandois, J., Sipp, D. \& Robinet, J.-C.2019bAnalysis and comparison of transonic buffet phenomenon over several three-dimensional wings. AIAA J.57 (1), 379-396.

[49] Parks, M. L., de Sturler, E., Mackey, G., Johnson, D. D. \& Maiti, S.2006Recycling Krylov subspaces for sequences of linear systems. SIAM J. Sci. Comput.28 (5), 1651-1674. · Zbl 1123.65022

[50] Plante, F., Dandois, J., Beneddine, S., Sipp, D. \& Laurendeau, E.2019aNumerical simulations and global stability analyses of transonic buffet and subsonic stall. In Proceedings of the 54th 3AF International Conference on Applied Aerodynamics, Paris, France, 2019. 3AF.

[51] Plante, F., Dandois, J. \& Laurendeau, E.2019bSimilarities between cellular patterns occurring in transonic buffet and subsonic stall. AIAA J. doi:.

[52] Reynolds, W. C. \& Hussain, A. K. M. F.1972The mechanics of an organized wave in turbulent shear flow. Part 3. Theoretical models and comparisons with experiments. J. Fluid Mech.54 (2), 263-288.

[53] Rivers, M., Quest, J. \& Rudnik, R.2018Comparison of the NASA Common Research Model European Transonic Wind Tunnel test data to NASA National Transonic Facility test data. CEAS Aeronaut. J.9 (2), 307-317.

[54] Saad, Y. \& Schultz, M. H.1986GMRES: a generalized minimal residual algorithm for solving nonsymmetric linear systems. SIAM J. Sci. Stat. Comput.7 (3), 856-869. · Zbl 0599.65018

[55] Sartor, F., Mettot, C. \& Sipp, D.2015Stability, receptivity and sensitivity analyses of buffeting transonic flow over a profile. AIAA J.53 (7), 1980-1993.

[56] Sartor, F. \& Timme, S.2017Delayed detached-eddy simulation of shock buffet on half wingbody configuration. AIAA J.55 (4), 1230-1240.

[57] Schwamborn, D., Gerhold, T. \& Heinrich, R.2006The DLR TAU-Code: recent applications in research and industry. In European Conference on Computational Fluid Dynamics, ECCOMAS CFD 2006. ECCOMAS.

[58] Sipp, D. \& Lebedev, A.2007Global stability of base and mean flows: a general approach and its applications to cylinder and open cavity flows. J. Fluid Mech.593, 333-358. · Zbl 1172.76318

[59] Sipp, D., Marquet, O., Meliga, P. \& Barbagallo, A.2010Dynamics and control of global instabilities in open-flows: a linearized approach. Trans. ASME Appl. Mech. Rev.63 (3), 030801.

[60] Sorensen, D. C.1992Implicit application of polynomial filters in a k-step Arnoldi method. SIAM J. Matrix Anal. Applics.13 (1), 357-385. · Zbl 0763.65025

[61] Steimle, P. C., Karhoff, D. C. \& Schröder, W.2012Unsteady transonic flow over a transport-type swept wing. AIAA J.50 (2), 399-415.

[62] Sugioka, Y., Koike, S., Nakakita, K., Numata, D., Nonomura, T. \& Asai, K.2018Experimental analysis of transonic buffet on a 3D swept wing using fast-response pressure-sensitive paint. Exp. Fluids59 (6), 108.

[63] Taira, K., Brunton, S. L., Dawson, S. T. M., Rowley, C. W., Colonius, T., McKeon, B. J., Schmidt, O. T., Gordeyev, S., Theofilis, V. \& Ukeiley, L. S.2017Modal analysis of fluid flows: an overview. AIAA J.55 (12), 4013-4041.

[64] Theofilis, V.2011Global linear instability. Annu. Rev. Fluid Mech.43 (1), 319-352. · Zbl 1299.76074

[65] Thormann, R. \& Widhalm, M.2013Linear-frequency-domain predictions of dynamic-response data for viscous transonic flows. AIAA J.51 (11), 2540-2557.

[66] Timme, S., Badcock, K. J., Wu, M. \& Spence, A.2012Lyapunov inverse iteration for stability analysis using computational fluid dynamics. In 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, AIAA Paper 2012-1563.

[67] Timme, S. \& Thormann, R.2016Towards three-dimensional global stability analysis of transonic shock buffet. In AIAA Aviation 2016 Forum, AIAA Paper 2016-3848.

[68] Tinoco, E. N., Brodersen, O., Keye, S., Laflin, K., Feltrop, E., Vassberg, J. C., Mani, M., Rider, B., Wahls, R. A., Morrison, J. H.et al.2018Summary data from the Sixth AIAA CFD drag prediction workshop: CRM cases. J. Aircraft55 (4), 1352-1379.

[69] Trefethen, L. N., Trefethen, A. E., Reddy, S. C. \& Driscoll, T. A.1993Hydrodynamic stability without eigenvalues. Science261 (5121), 578-584. · Zbl 1226.76013

[70] Vassberg, J. C., DeHaan, M. A., Rivers, S. M. \& Wahls, R. A.2018Retrospective on the common research model for computational fluid dynamics validation studies. J. Aircraft55 (4), 1325-1337; also in 26th AIAA Applied Aerodynamics Conference, AIAA Paper 2008-6919.

[71] Xu, S., Timme, S. \& Badcock, K. J.2016Enabling off-design linearised aerodynamics analysis using Krylov subspace recycling technique. Comput. Fluids140, 385-396. · Zbl 1390.76267