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A nonlinear modeling approach using weighted piecewise series and its applications to predict unsteady flows. (English) Zbl 1349.76149

J. Comput. Phys. 318, 58-84 (2016).

Summary: To preserve nonlinearity of a full-order system over a range of parameters of interest, we propose an accurate and robust nonlinear modeling approach by assembling a set of piecewise linear local solutions expanded about some sampling states. The work by Rewienski and White [1] on micromachined devices inspired our use of piecewise linear local solutions to study nonlinear unsteady aerodynamics. These local approximations are assembled via nonlinear weights of radial basis functions. The efficacy of the proposed procedure is validated for a two-dimensional airfoil moving with different pitching motions, specifically AGARD's CT2 and CT5 problems [27], in which the flows exhibit different nonlinear behaviors. Furthermore, application of the developed aerodynamic model to a two-dimensional aero-elastic system proves the approach is capable of predicting limit cycle oscillations (LCOs) by using AGARD's CT6 [28] as a benchmark test. All results, based on inviscid solutions, confirm that our nonlinear model is stable and accurate, against the full model solutions and measurements, and for predicting not only aerodynamic forces but also detailed flowfields. Moreover, the model is robust for inputs that considerably depart from the base trajectory in form and magnitude. This modeling provides a very efficient way for predicting unsteady flowfields with varying parameters because it needs only a tiny fraction of the cost of a full-order modeling for each new condition–the more cases studied, the more savings rendered. Hence, the present approach is especially useful for parametric studies, such as in the case of design optimization and exploration of flow phenomena.

MSC:

76G25 General aerodynamics and subsonic flows

Keywords:

modeling of nonlinear dynamics with parametric inputs; weighted piecewise linear (WPL) model; unsteady flow; limited cycle oscillations

Software:

AUSM; TAPENADE

Full Text: DOI

References:

[1] Rewienski, M.; White, J., Improving trajectory piecewise-linear approach to nonlinear model order reduction for micromachine devices using an aggregated projection basis, IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst., 24, 2, 155-170, (2003)

[2] Silva, W., Identification of nonlinear aeroelastic systems based on the Volterra theory: progress and opportunities, Nonlinear Dyn., 39, 1-2, 25-62, (2005) · Zbl 1104.70014

[3] Sirovich, L., Turbulence and the dynamics of coherent structures. part I: coherent structures, Q. Appl. Math., 45, 3, 561-571, (1987) · Zbl 0676.76047

[4] Romanowski, M., Reduced order unsteady aerodynamic and aeroelastic models using Karhunen-loeve eigenmodes, (1996), AIAA-96-3981

[5] Moore, B. C., Principle component analysis in linear system controllability, observability, and model reduction, IEEE Trans. Autom. Control, 26, 1, 17-32, (1981) · Zbl 0464.93022

[6] Laub, A. J.; Heath, M. T.; Page, C. C.; Ward, R. C., Computation of system balancing transformations and other applications of simultaneous diagonalization algorithms, IEEE Trans. Autom. Control, 32, 2, 115-122, (1987) · Zbl 0624.93025

[7] Willcox, K.; Peraire, J., Balance model reduction via the proper orthogonal decomposition, AIAA J., 40, 11, 2323-2330, (2002)

[8] Rowley, C. W., Model reduction for fluids using balanced proper orthogonal decomposition, Int. J. Bifurc. Chaos, 15, 3, 997-1013, (2005) · Zbl 1140.76443

[9] Ma, Z.; Ahuja, S.; Rowley, C. W., Reduced order models for control of fluids using the eigensystem realization algorithm, Theor. Comput. Fluid Dyn., 25, 1, 233-247, (2011) · Zbl 1272.76103

[10] Brunton, S. L.; Rowley, C. W.; Williams, D. R., Reduced-order unsteady aerodynamic models at low Reynolds numbers, J. Fluid Mech., 724, 203-233, (2013) · Zbl 1287.76078

[11] Hascoët, L.; Pascual, V., Tapenade 2.1 User's guide, (2004), INRIA, Technical report 0300

[12] Gu, C.; Roychowdhury, J., Model reduction via projection onto nonlinear manifolds with application to analog circuits and biochemical systems, (IEEE/ACM International Conference on Computer-Aided Design, (2008)), 85-92

[13] Gratton, D.; Willcox, K., Reduced-order, trajectory piecewise-linear models for nonlinear computational fluid dynamics, (34th AIAA Fluid Dynamics Conference and Exhibit, (2004)), AIAA 2004-2329

[14] Jesmani, M.; Hosseini, B.; Chalaturnyk, R., Use of streamlines in development and application of a linearized reduced-order reservoir model, (9th International Geostatistics Congress, (2012))

[15] He, J.; Saetrom, J.; Durlofsky, L. J., Enhanced linearized reduced-order models for subsurface flow simulation, J. Comput. Phys., 230, 23, 8313-8341, (2011) · Zbl 1337.76064

[16] Rugh, W. S.; Shamma, J. S., Research on gain scheduling, Automatica, 36, 1401-1425, (2000) · Zbl 0976.93002

[17] Shamma, J. S.; Athans, M., Gain scheduling: potential hazards and possible remedies, IEEE Control Syst., 12, 3, 101-107, (1992)

[18] Johansen, T. A.; Murray-Smith, R., The operating regime approach to nonlinear modeling and control, (Murray-Smith, R.; Johansen, T. A., Multiple Model Approaches to Modelling and Control, (1997), Taylor-Francis), Ch. 1

[19] Nichols, R.; Reichert, R.; Rugh, W., Gain-scheduling for H-infinity controllers: a flight control example, IEEE Trans. Control Syst. Technol., 1, 2, 69-79, (1993)

[20] Marcos, A.; Balas, G. J., Development of linear-parameter-varying models for aircraft, J. Guid. Control Dyn., 27, 2, 218-228, (2004)

[21] Chaturantabut, S.; Sorensen, D., Nonlinear model reduction via discrete empirical interpolation, SIAM J. Sci. Comput., 32, 5, 2737-2764, (2010) · Zbl 1217.65169

[22] Everson, R.; Sirovich, L., The Karhunen-loeve for gappy data, J. Opt. Soc. Am. A, 12, 1657-1664, (1995)

[23] Zhou, Y., Model reduction for nonlinear dynamical systems with parametric uncertainties, (2012), MIT, Masters thesis

[24] Carlberg, K.; Farhat, C.; Cortial, J.; Amsallam, D., The GNAT method for nonlinear model reduction: effective implementation and application to computational fluid dynamics and turbulent flows, J. Comput. Phys., 242, 623-647, (2013) · Zbl 1299.76180

[25] Yao, W.; Liou, M.-S., Reduced-order modeling for flutter/LCO using recurrent artificial neural network, (14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, (2012)), AIAA 2012-5446

[26] Buhmann, M. D., Radial basis functions: theory and implementations, (2003), Cambridge University Press · Zbl 1038.41001

[27] Landon, R. H., NACA 0012 oscillatory and transient pitching, (January 1982), AGARD, Dataset 3

[28] Davis, S. S., NACA 64A010 (NASA ames model) oscillatory pitching, (January 1982), AGARD, Dataset 2

[29] Liou, M.-S., A sequel to AUSM, part II: AUSM+-up, J. Comput. Phys., 214, 1, 137-170, (2006) · Zbl 1137.76344

[30] Durand, E., Time domain modeling of unsteady aerodynamic forces on a flapping airfoil, (1998), MIT, Master thesis

[31] Von Karman, T.; Sears, W. R., Airfoil theory for non-uniform motion, J. Aeronaut. Sci., 5, 10, 379-390, (1938) · Zbl 64.1461.04

[32] Garrick, I. E., Propulsion of a flapping and oscillating airfoil, (1936), NACA report 567 · Zbl 62.1583.01

[33] Thomas, J. P.; Dowell, E. H.; Hall, K. C., Nonlinear inviscid aerodynamic effects on transonic divergence, flutter, and limit-cycle oscillation, AIAA J., 40, 4, 639-645, (2002)

[34] Pierce, N. A.; Alonso, J. J., Efficient computation of unsteady viscous flow by an implicit preconditioned multi-grid method, AIAA J., 36, 3, 401-408, (1998)

[35] McMullen, M.; Jameson, A.; Alonso, J. J., Application of a non-linear frequency domain solver to the Euler and Navier-Stokes equations, (40th AIAA Aerospace Sciences Meeting & Exhibit, (2002)), AIAA 2002-0120

[36] Liou, M.-S.; Yao, W., A versatile nonlinear method for predictive modeling, (22nd AIAA Computational Fluid Dynamics Conference, (2015)), AIAA 2015-2453