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Fumio Fujii, Masato Tanaka, Takashi Sasagawa, Ryuji Omote

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Computational Two-mode Asymptotic Bifurcation Theory Combined with Hyper Dual Numbers and Applied to Plate/Shell Buckling Fumio FUJII^a, Masato TANAKA^{b*}, Takashi SASAGAWA^b and Ryuji OMOTE^b ^a Department of Mechanical Engineering, Gifu University (Emeritus), Gifu 501-1193, Japan ^b Toyota Central R&D Labs., Inc., 41-1 Yokomichi, Nagakute-shi, Aichi 480-1192, Japan

10 Abstract

For error-free computation of higher-order derivatives of a complex mathematical expression composed of elementary functions, hyper-dual numbers (HDNs) are receiving close attention in computational engineering and sciences. Differently from conventional finite differences, HDNs numerically evaluate, for instance, the exact first-order and second-order derivatives of the stiffness matrix with respect to nodal degrees-of-freedom (dof) in nonlinear finite element (FE) analysis.

16 One of the most promising applications of HDNs is the asymptotic structural stability theory, which usually requires, in conventional series expansions, an unrealistically large number of second-order 17 derivative of the stiffness matrix to predict the instability behavior of large-scale FE models. This 18 19 computational bottleneck may be avoided along with so-called classical Lyapunov-Schmidt-Koiter 20 condensation by a novel idea proposed in the present study. The proposed two-mode computational 21 asymptotic theory is implementable in engineering practice to algebraically identify snap-through and 22 path-branching in stability problems. One more associated innovation is a graphical solution of two 23 simultaneous equations resulting from the asymptotic expansions. This sophisticated solution idea 24 utilizing a popular mathematical tool (MATLAB) is widely applicable to quickly visualize the location 25 and number of existing solutions.

26 More specifically, the present paper formulates a two-mode asymptotic bifurcation theory in 27 combination with HDNs and presents an examination of the proposed computational theory on stability 28 problems of plates and shells. Near a precisely computed singular point on the equilibrium path, the 29 incremental displacement field is represented in two modes: θ and δ . One mode (θ) is the critical 30 eigenvector corresponding to the zero eigenvalue of the singular tangent stiffness matrix. The other one 31 (δ) is a linear combination of all other non-critical eigenvectors. θ and δ respectively constitute the 32 homogeneous and particular solutions of the linearized equilibrium equations established in the singular 33 point. Two perturbation parameters, σ and τ , work as weights of θ and δ , respectively, to find possible 34 equilibria around the singular point. The nonlinear equilibrium equations are expanded into asymptotic 35 series of σ and τ to use HDNs to compute 20 coefficients including first-order and second-order 36 derivatives of the stiffness matrix in polynomials. The simultaneous polynomial equations of σ and τ are 37 solved by using the MATLAB graphic operations.

The obtained results in numerical examples well predict the stability behavior in excellent agreement with solutions available in conventional FE stability analysis. The two-mode asymptotic bifurcation theory combined with HDNs is sufficient to diagnose snap-through, asymmetric branching, unstable and stable symmetric bifurcation in structural stability problems.

> * Corresponding author. E-mail address: <u>tanamasa@mosk.tytlabs.co.jp</u> (M. Tanaka)

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