Advances in Aircraft and Spacecraft Science, *Vol. 5, No. 3 (2018) 335-348*
DOI: https://doi.org/10.12989/aas.2018.5.3.335

Novel aspects of elastic flapping wing: Analytical solution for inertial forcing

Hadi Zare[a], Seid H. Pourtakdoust*[1] and Ariyan Bighashdel[b]

Center of Excellence in Aerospace Systems, Department of Aerospace Engineering, Sharif University of Technology, Azadi Street, Tehran, Iran

(Received June 14, 2017, Revised September 13, 2017, Accepted October 9, 2017)

Abstract. The structural dynamics (SD) behavior of Elastic Flapping Wings (EFWs) is investigated analytically as a novel approach in EFWs analysis. In this regard an analytical SD solution of EFW undergoing a prescribed rigid body motion is initially derived, where the governing equations are expressed in modal space. The inertial forces are also analytically computed utilizing the actuator induced acceleration effects on the wing structure, while due to importance of analytical solution the linearity assumption is also considered. The formulated initial-value problem is solved analytically to study the EFW structural responses, where the effect of structure-actuator frequency ratio, structure-flapping frequency ratio as well as the structure damping ratio on the EFW pick amplitude is analyzed. A case study is also simulated in which the wing is modeled as an elastic beam with shell elements undergoing a prescribed sinusoidal motion. The corresponding EFW transient and steady response in on-off servo behavior is investigated. This study provides a conceptual understanding for the overall EFW SD behavior in the presence of inertial forces plus the servo dynamics effects. In addition to the substantial analytical results, the study paves a new mathematical way to better understanding the complex role of SD in dynamic EFWs behavior. Specifically, similar mathematical formulations can be carried out to investigate the effect of aerodynamics and/or gravity.

Keywords: flapping wing; modeling; structural dynamics; aeroelasticity; inertial forcing

1. Introduction

Flapping aerial vehicles (FAVs) have attracted worldwide interest for their possible applications in a wide range of activities, such as monitoring and surveillance. FAVs use flapping wing mechanism to fly, while simultaneously producing thrust and lift. Both bird-like and insect-like flyers utilize flexible flapping wings which have anisotropic flexibilities in chordwise and spanwise directions (Shyy *et al.* 1999). Based on their structures, flapping wings undergo moderate to large flexible deformation during flight (Wootton 1992).

The flexibility has a significant effect on the FAVs aerodynamic loading (Smith 1995, Olivier

*Corresponding author, Professor, E-mail: pourtak@sharif.edu
[a]Ph.D. Candidate, E-mail: h_zare@ae.sharif.ir
[b]M.Sc., E-mail: bighashdel_a@ae.sharif.ir

http://www.techno-press.org/?journal=aas&subpage=7 ISSN: 2287-528X (Print), 2287-5271 (Online)

Meirovitch, L. and Tuzcu, I. (2003), *Integrated Approach to the Dynamics and Control of Maneuvering Flexible Aircraft*, NASA/CR-2003-211748, National Aeronautics and Space Administration, Langley Research Center.

MSC Nastran (2010), *MSC Nastran 2010 User's Manual*, MSC.Software Corporation, Sant Ana, U.S.A.

Nakata, T. and Liu, H. (2012), "A fluid-structure interaction model of insect flight with flexible wings", *J. Comput. Phys.*, **231**(4), 1822-1847.

Ogata, K. (2010), *Modern Control Engineering*, Prentice Hall, Upper Saddle River, New Jersey, U.S.A.

Olivier, M. and Dumas, G. (2016), "Effects of mass and chordwise flexibility on 2D self-propelled flapping wings", *J. Flu. Struct.*, **64**, 46-66.

Platus, D. (1992), "Aeroelastic stability of slender, spinning missiles", *J. Guid. Contr. Dyn.*, **15**(1), 144-151.

Pourtakdoust, S. and Assadian, N. (2004), "Investigation of thrust effect on the vibrational characteristics of flexible guided missiles", *J. Sound Vibr.*, **272**(1), 287-299.

Pourtakdoust, S.H. and Aliabadi, S.K. (2012), "Evaluation of flapping wing propulsion based on a new experimentally validated aeroelastic model", *Sci. Iran.*, **19**(3), 472-482.

Rizzi, S.A. and Muravyov, A.A. (2002), *Equivalent Linearization Analysis of Geometrically Nonlinear Random Vibrations Using Commercial Finite Element Codes*, NASA/TP-2002-211761, National Aeronautics and Space Administration.

Shyy, W., Berg, M. and Ljungqvist, D. (1999), "Flapping and flexible wings for biological and micro air vehicles", *Progr. Aerosp. Sci.*, **35**(5), 455-505.

Singh, B. and Chopra, I. (2007). "An aeroelastic analysis for the design of insect-based flapping wings", *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, Hawaii, U.S.A., April.

Smith, M. (1995), "The effects of flexibility on the aerodynamics of moth wings-towards the development of flapping-wing technology", *Proceedings of the 33rd Aerospace Sciences Meeting and Exhibit*, Reno, NV, U.S.A., January.

Wilson, N. and Wereley, N. (2007), "Experimental investigation of flapping wing performance in hover", *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, Hawaii, U.S.A., April.

Wootton, R.J. (1992), "Functional morphology of insect wings", *Ann. Rev. Entomol.*, **37**(1), 113-140.

Yeo, D., Atkins, E.M., Bernal, L.P. and Shyy, W. (2013), "Experimental characterization of lift on a rigid flapping wing", *J. Aircr.*, **50**(6), 1806-1821.

Zhao, L., Huang, Q., Deng, X. and Sane, S.P. (2010), "Aerodynamic effects of flexibility in flapping wings", *J. Roy. Soc. Interf.*, **7**(44), 485-497.

EC