

Effects of Spanwise Flexibility on Performance of Flapping Flyers in Forward Flight

Deepa Kodali¹, Cory Medina¹, Chang-kwon Kang^{1*}, Hikaru Aono²

¹Department of Mechanical and Aerospace Engineering, University of Alabama in Huntsville, AL 35899, USA.

²Department of Mechanical Engineering, Tokyo University of Science, Tokyo, Japan 125-8585

*Corresponding author: chang-kwon.kang@uah.edu

Supplementary Information

1. Sensitivity analyses of the aeroelastic responses

The sensitivity of the aeroelastic response of the goose and passerine models on the variations in thickness h_s , wing density ρ_s and Young's modulus E is illustrated in figure S1. The normalized tip displacement amplitude u_a/h_a because the spanwise wing bending u/h_a shown in figure 6 in the main text is similar for the two bird models. The wing thickness, wing density, and Young's modulus for the two bird models are varied by 15% with a change of -15%, -10%, -5%, 5%, 10% and 15% of actual parameters. The plunge amplitude h_a for these cases is chosen in such a way that for every aspect ratio AR , the resulting relative wing tip amplitude w_a matches the corresponding observed stroke amplitudes for these birds reported in the literature (section 4 in the main text).

The results in figure S1 suggest that the current aerodynamic model is sensitive to the considered structural parameters. A variation in thickness and density yield noticeable differences in u_a/h_a and AR . The aspect ratio changes with variations in E , however u_a/h_a remains invariant. This invariance can be explained as follows.

The dependence of the relative wing deformation w on the Young's modulus E is shown in equations (8) and (9) in the main text. In particular, E only appears in the definition of the frequency ratio f_n^* through $\Pi_1 = Eh_s^{*3}/(12\rho_f U^2)$. Additionally, AR only appears in f_n^* . Since the employed approach aims to preserve w^* to match the observed flapping angle, AR can be adjusted for any variation in E , such that E/AR^4 and, hence, f_n^* and all other terms in equation (8)

of the main text remain invariant.

Although we assume an equal density ratio ρ^* for both the birds, the reduced frequency k and thickness ratio h_s^* are different for both flyers as shown in table 3 in the main text. Because of different k and h_s^* , different tip amplitudes are obtained for the passerine ($u_a = 0.12$ m) and goose ($u_a = 0.48$ m) models. However, the tip amplitude when normalized with plunge amplitude results in almost the same magnitudes, i.e. $u_a/h_a = 10$ (passerine) vs $u_a/h_a = 9.4$ (goose). The tip phase lag ϕ_{tip} is also slightly different: 102.2° (passerine) vs 99.8° (goose). Furthermore, at resonance the first order bending mode is dominant as shown in figures 4(c) and 5(c) in the main text. The combination of the first order bending mode being dominant and similar values of u_a/h_a have resulted in the similar u/h_a bending snapshots for the two bird wing models in figure 6 in the main text.

To illustrate that the current model can yield a qualitatively different solution, the following parameters are considered for the goose model: wing thickness $h_s = 0.966$ mm, wing density $\rho_s = 2000$ kg/m³ and Young's modulus $E = 5$ GPa. Figure S2 clearly shows that the resulting structural response is qualitatively different than the results for the goose model (figure 6(b) in the main text). The resulting aeroelastic response is shown in figure S3. Both the first and the second order modes are now dominant, which explains the different wing shapes shown in figure S2. Interestingly, the optimal aspect ratio is 5.3, similar to the actual aspect ratio of 5.4 and the optimal aspect ratio for the goose model ($AR = 5.5$).