# Multibody Dynamics and Optimisation of Flapping Wing Vehicle for Mars Atmospheric Flight

Zdravko Terze, Marko Kasalo, Dario Zlatar, Pierangelo Masarati
and Alessandro Cocco

June 9, 2024

The 7th International Conference on Multibody System Dynamics
June 9-13, 2024, Madison, WI, USA

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**Terze Zdravko[1], Kasalo Marko[1], Zlatar Dario[1], Masarati Pierangelo[2], Cocco Alessandro[2*]**

[1]Faculty of Mechanical Engineering
and Naval Architecture,
University of Zagreb
Ivana Lucica 5, 10000, Zagreb,
Croatia
[zdravko.terze, marko.kasalo,
dario.zlatar]@fsb.hr

[2]Department of Aerospace Science and
Technology,
Politecnico di Milano
via La Masa 34, 20156, Milano,
Italy
[pierangelo.masarati,
alessandro.cocco]@polimi.it
* Currently at the University of Maryland

## Introduction

Martian thin atmosphere renders atmospheric flight significantly more challenging than flight on Earth. On the contrary to the conventional rotary and fixed wing configurations that have limited utilization due to their inefficiency in Low Reynolds flight regime, atmospheric flight on Mars by using flapping wing propulsion/lift gaining technique is a promising concept. Starting from a biomimetic analysis of energy efficient flight on our planet – that suggests that the flapping wing technique could be the optimal way for performing efficient and manoeuvrable flight on Mars as well – further analysis of the pertinent flight physics just proves this hypothesis [5].

Although designing of flapping wing vehicles (FWV) has reached certain level of maturity, current design of FWV is still very much dependent on the experimental activities, not relying extensively on the computational models. Certainly, one of the reasons for this is challenging modelling of the FWV flight physics (that includes highly unsteady aerodynamics, wing-fluid interactions, high flapping frequency effects etc.), but also numerical inefficiency of the standard computational procedures, mostly based on the continuum discretisation of the ambient fluid and loosely coupled co-simulations between solid and fluid part of the system [4]. Indeed, numerical inefficiency and time-consuming characteristics of such 'high-fidelity' numerical methods restrict their utilisation mostly to case-by-case simulation campaigns, preventing their usage within the effective optimisation procedures that would allow for multicriterial design optimisation of FWV.

To this end, objective of the paper is to present numerically efficient computational model and optimisation-based validation tool that will allow for 'automated' testing of the basic FWV design principles how to fly on Mars. The algorithm is based on reduced-order FSI (fluid- structure interaction) and quasi-steady model for a fruit fly-like aerial vehicles [6], combined with the Discrete Mechanics and Optimal Control (DMOC) approach [2].

## Multibody model and optimisation procedure

By adopting flapping wing propulsion concept – which needs to operate within the range of low Reynolds numbers pertinent to Mars atmospheric flight – baseline configurations with two or four symmetrically placed wings are selected as the most convenient combination [3]. The kinematics of the wings is defined by two sequential rotations, i.e. stroking and pitching. Deviation/plunging angle is omitted in the analysis because it considerably increases unsteadiness of the flapping wing aerodynamics, without contributing significantly to the total value of the lift and drag forces measured over one complete cycle [1]. For the first run of the preliminary conceptual design based on the developed models only hovering and forward flight scenarios are analyzed.

The impact of the energy storage elements (i.e. mechanical springs) on the motion efficiency of the FWV's flight is also analyzed within the conducted numerical experiments. This is due to the fact that system elaborated passive dynamics is one of the crucial features of the overall successful dynamical designs. To this end, two computational scenarios are adopted i.e one with and one without spring elements involved. The behavior of the progressive spring is modeled by utilizing a polinomial function, while the stiffness coefficient (defined as an optimization parameter) is calculated for each case by the optimization algorithm.

Finally, vehicle mass is varied from 10 g to 10 kg by utilising discrete steps of 10 g (from 10 g to 200 g), 100 g (from 200 g to 2 kg) and 0.5 kg (from 2 kg to 10 kg). Vehicles with larger masses were not considered due to other design limitations.

## Results

Acquired solutions have proven Mars FWV feasibility for various combinations of flapping frequencies and wing lengths. Figure 1 (a) depicts comparison of selected two-winged vehicle configurations within frequency-wing length design subspace. Additionally, isolated feasible solutions for 250 g vehicle, as well as their relation to average power and stroke amplitude, are presented in Figure 1 (b). Finally, it can be observed that larger amplitudes with lower frequencies are more energy efficient than smaller amplitudes with higher frequencies, as well as larger wings with lower frequencies when compared to smaller wings with higher frequencies.

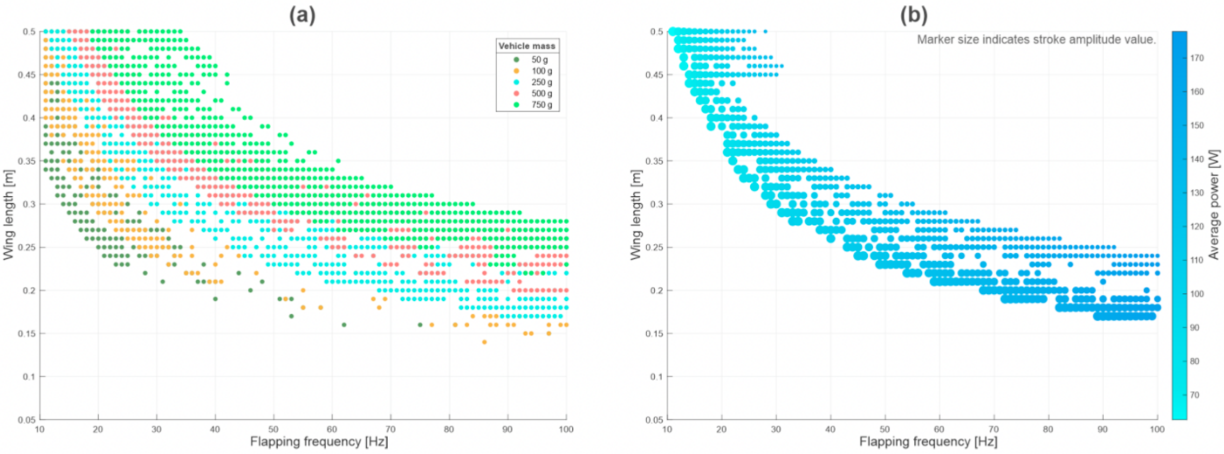

Figure 1: Feasible combinations of wing lengths and flapping frequencies for selected two-winged Mars FWV configurations. (a) Comparison of most representative Mars FWV baseline designs. (b) Isolated solutions for 250 g vehicle with indicated relation to average power (marker color) and stroke amplitude (marker size).

## Acknowledgments

This work has been fully supported by European Space Agency (ESA) under the project 'Flapping Flight on Mars and Venus' (Contract No. 4000136208/21/NL/SC).

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