Ref. Ares(2021)1386402 - 20/02/2021

D2.1 Flight Control System Layout

GA number: 815058
Project acronym: FLIPASED
Project title: FLIGHT PHASE ADAPTIVE AEROSERVO-ELASTIC AIRCRAFT DESIGN METHODS
Funding Scheme:H2020 **ID:** MG-3-1-2018
Latest version of Annex I: 1.1 released on 12/04/2019
Start date of project: 01/09/2019 **Duration:** 40 Months

Lead Beneficiary for this deliverable: SZTAKI
Last modified: 10/11/2020 **Status:** Delayed
Due date: 31/10/2020

Project co-ordinator name and organisation: Bálint Vanek, SZTAKI
Tel. and email: **+36 1 279 6113** vanek@sztaki.hu
Project website: www.flipased.eu

Dissemination Level		
PU	Public	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

“This document is part of a project that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 815058.”

Table of contents

Glossary

1 Executive Summary

The present report details the flight control system layout. By this, one intends the structure of the proposed control architecture and the list of control functions to be constructed and integrated within the global MDO process. This MDO global architecture is illustrated in Figure 1. The control block is as the bottom right in purple. It closely interacts with the "structure" block trough the "control surface" and "sensors". Indeed, the "controls" connects the sensors and actuators with the control law to be designed. This latter is nothing but a mathematical difference equation or program, that adjusts control surfaces accordingly to sensed physical data. In practice, to construct such a mathematical law or program, control functions should be linked to other functional features, such as the aero-models and mission planning. The process chain links, as treated in the project, is given in Figure 2, with focus on control functions.

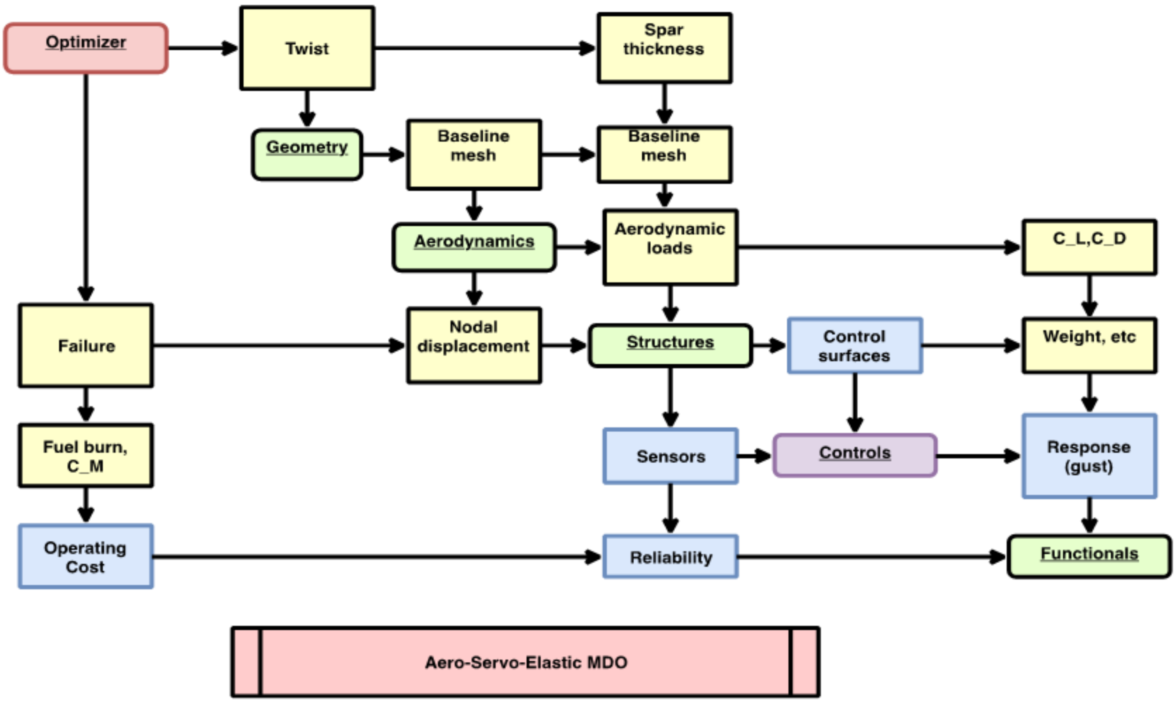

Figure 1: MDO process overview. Control is the purple bottom right box.

This structure is subject to amendments and modifications along the project. Indeed, a solution can be dropped or replaced by another one if functions remained unchanged. However, the main ideas are presented here.

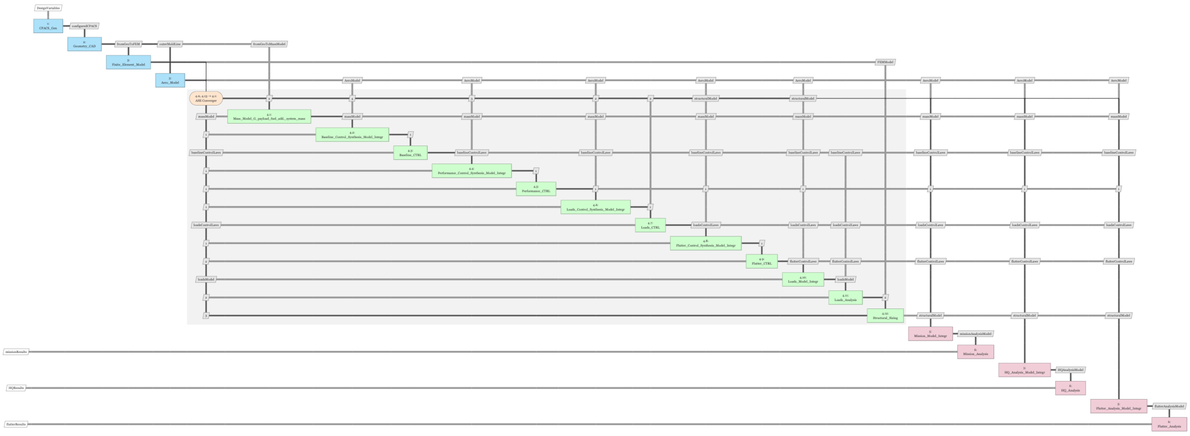

Figure 2: MDO process overview and focus on the control steps.

Figure 3: FLiPASED logo

2 Introduction

2.1 Context of FLiPASED WP2

Within the FLiPASED project, the Work Package 2 (WP2) is dedicated to the feedback control functions construction. The main objective of the WP is to develop a bundle of functions allowing to design the control functions in an automated manner, in order to be included in the global Multi Disciplinary Optimisation (MDO) process. This MDO being the central objective of FLiPASED.

This WP involves three research groups, the DLR, ONERA and SZTAKI. More specifically, the people involved are:

DLR	M. Pusch (MP) and M. Wuestenhagen (MW)
ONERA	P. Vuillemin (PV) and C. Poussot-Vassal (CPV)
SZTAKI	T. Luspay (TL) and B. Takarics (BT)

2.2 Purpose of the report

The present report details the flight control system layout. By this, one intends the structure of the proposed control architecture and the list of control functions to be constructed and integrated within the global MDO process.

3 Control architecture and layout

3.1 Expected closed-loop structure

Generally, aircraft manufacturer control design workflow follows what we can call a frequency grid approach. This approach consists in designing different controllers, through a frequency guideline. Each of them address a phenomena an aircraft is faced during its operation. Within the overall MDO process philosophy and in this WP, we aim at following this approach. With reference to Figure 4, one may notice that different phenomena (flight, loads...) usually occurs at different frequencies. These frequencies are dependent on the geometry and structure of the aircraft. In the considered case, one may expect even more blending between each phenomenon. Still the big picture remains valid. This sequential control structure will be kept in mind in the WP2 flow to stick to industrial and practical expectations.

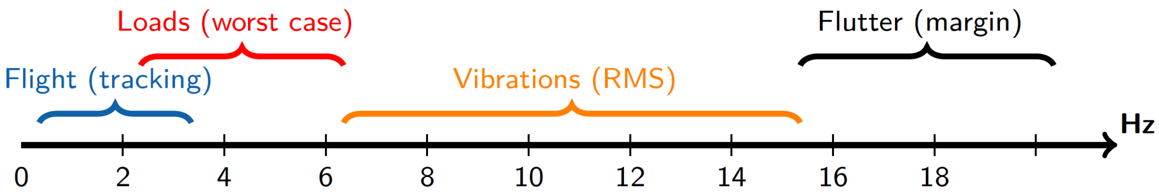

Figure 4: Frequency grid of the physical phenomena occurring over an aircraft. Ranges and values are different from an aircraft to an other.

As a matter of consequence, the closed-loops one is intended to develop is presented as in Figure 5, where each function in cascaded with the other. More specifically, the flight controller aims at focusing on the handling qualities and manoeuvrability while the load control focuses either on maneuver of gust phenomena. One underlying objective of this WP2 is to design such control law, but not only. As the complete process addressed in the FLiPASED project is an MDO one, aircraft parameters $\mathbf{p}$ will also be tuned and optimised, together with the control. These control law are usually designed following the increasing frequency physics: first flight control, then load, etc.

As presented in Figures 4 and 5, the flight control system layout will gather a set of multiple functions. Each function should be independently designed without affecting the others. Moreover, as the functions are connected but somehow with different objectives, we will consider designing them with the following sequence:

1. Flight control, a flight oriented control
2. MLA, a maneuver load alleviation control

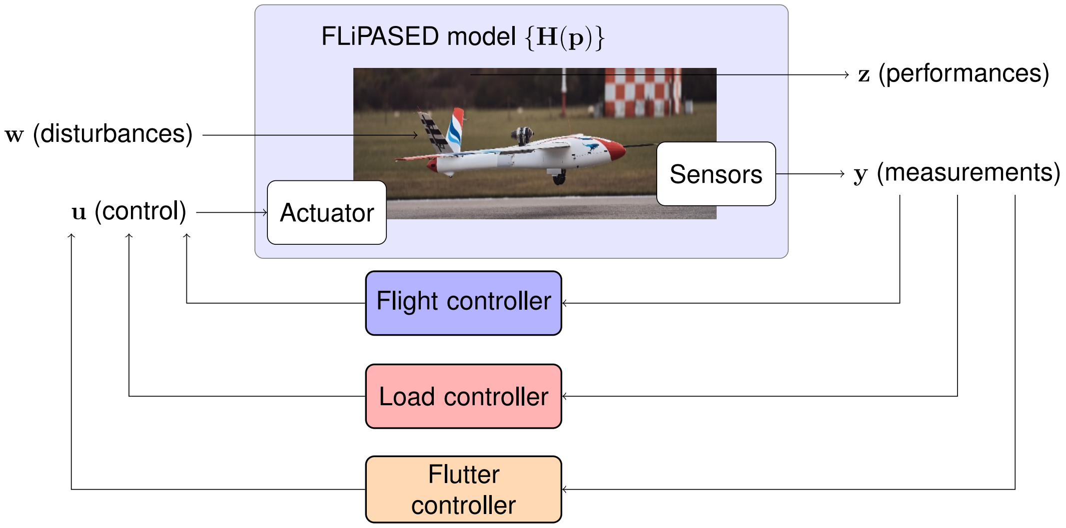

Figure 5: Multiple control loops considered in the WP2.

3. GLA, a gust load alleviation control
4. Flutter, a flutter shield control

As all these phenomena are specific and operate at different frequencies, the models $\mathbf{H}(\mathbf{p})$ (where $\mathbf{H}$ is a complex linear map and $\mathbf{p}$ the parameter vector) involved in the design optimisation step may vary from a function to an other. By this one intends that even if one single global model is provided by the upper WP, different sub models may be constructed within this WP, accordingly to the considered phenomena and control design objective.

3.2 Input-output data description

Without detailing the typical inputs and outputs, the following Figure 6, gathers the main input and output data that has to be exchanged from the upper WP to the lower ones. The global interconnection is referenced in the main project document.

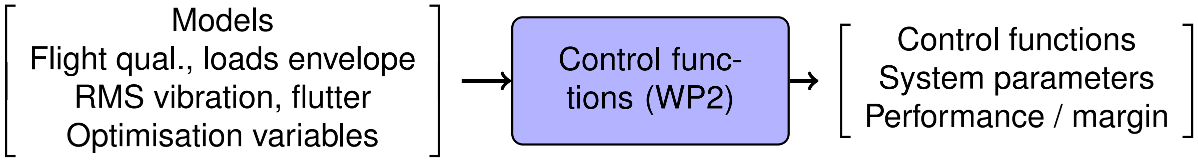

Figure 6: Data exchanges within WP2.

3.2.1 Inputs

When dealing with control, the main input to be considered are the model, denoted $\mathbf{H}$ or $\mathbf{H}(\mathbf{p})$, when considering a parametric one, or $\{\mathbf{H}_i\}_{i=1}^{n_s}$ if a set of models is given. More specifically, the following inputs are expected.

- Linear (or nonlinear) dynamical models / simulators (finite or infinite dimension)
- Gust load envelope (nominal)
- Maneuver load envelope (nominal)
- Flutter-free envelope (nominal)
- Sensors/actuators dynamical characteristics and degree of freedom (such as location, speed...)

3.2.2 Outputs

As rooted on the above inputs, the WP2 aims at delivering both *functions and results*. The former being *functions*, represent features developed that can be called within the MDO process, to get optimised aircraft (including control laws and optimised aircraft design parameters). The latter being *results*, represent tag (such as robustness, stability, ...) that can be used to decide the quality of the actual design and derive some optimisation directions. The following gives the main outputs, plus some potentially fruitful ones.

- Control functions (Flight / MLA-GLA / Flutter)
- Performance metrics
- System parameters

\+ Reduced models (suitable for control and analysis)

3.3 Functional task sharing

The organisation between the three research groups involved in this WP2 follows the Table 1. This table presents the functions to develop and the holder of each of them. As a preliminary report, this table should be amended and filled during the project life. Still, as this point, checking all these tasks will result in a complete tool for fast aircraft control law and parameter optimisation.

WP	Title	Function	Holder
2.1 Modelling	Construction linear ROM	✓ Order reduction automatic guess	ONERA
		✓ Model order reduction from finite realisation	SZTAKI
		✓ Model order reduction from infinite realisation or transfer function	ONERA
	Construction parametric ROM	✓ From bundle of LTI models	SZTAKI
	Construction LPV ROM	✓ From bundle of LTI models	SZTAKI
	Model integration	✓ Intergate the models within the MDO tool	SZTAKI
2.2 Control	Flight qualities	✓ Design using INDI	DLR
		✓ Design using scheduled PID	SZTAKI
	GLA	✓ Design using LTI $\mathcal{H}_\infty$ control	DLR
		✓ Design using LTI Modal control	DLR
		✓ Design using LPV control	SZTAKI
	MLA	✓ Design using (linear) MPC control	SZTAKI
	Flutter control	✓ Design using LTI $\mathcal{H}_\infty$ control	DLR
		✓ Design using LTI Modal control	SZTAKI
		✓ Design using LPV control	DLR
	Others	✓ Actuators / sensors placement	DLR
		✓ Wing shape control for optimal drag configuration	SZTAKI
2.3 Analysis	Performances	✓ Assessment function of the performances	ONERA
		✓ HiL	SZTAKI
		✓ Worst case analysis	SZTAKI
		✓ Actuator limits	DLR
		✓ $\mathcal{H}_\infty$ norm computation (large-scale and delayed models)	ONERA

Table 1: Task sharing.

Following Table 1, let us now detail the input outputs of each line, by linking if possible, to the CPACS formalism, adopted for the global MDO process detailed after.

3.4 Modelling (2.1)

Order reduction automatic guess (Matlab/Simulink data)

Objective: Guess a reduction order in view of low complexity model construction.

> **Input:**
>
> - A linear dynamical model description denoted $\mathbf{H}$, linking n_u inputs to n_y outputs, given as
>   - A linear state-space model (first or second order)
>   - A transfer function (rational or irrational)
>   - A time-domain simulator
>   - A frequency-domain simulator
>
> **Output:**
>
> - A guessed reduction order r or upper bound (scalar)

Model order reduction from a finite realisation (Matlab data)

Objective: Reduce the dynamical model complexity to simplify and fasten the control design optimisation.

> **Input:**
>
> - A linear dynamical model description denoted $\mathbf{H}$, linking n_u inputs to n_y outputs, given as
>   - A linear state-space model (first or second order differential equations)
>   - A transfer function (rational)
> - A reduction order r (scalar)

> **Output:**
>
> - A n_u inputs to n_y outputs reduced order rational model $\hat{\mathbf{H}}$

Model order reduction from an infinite realisation or transfer function (Matlab/Simulink data)

Objective: Construct a low complexity rational model from an irrational one to be adapted to control methods.

> **Input:**
>
> - A linear dynamical model description denoted $\mathbf{H}$, linking n_u inputs to n_y outputs, given as
>   - A linear state-space model (first or second order differential equations, including irrational terms)
>   - A transfer function (rational or irrational)
>   - A time-domain simulator
>   - A frequency-domain simulator
> - A reduction order r (scalar)
>
> **Output:**
>
> - A n_u inputs to n_y outputs reduced order rational model $\hat{\mathbf{H}}$

Parametric reduced order model (Matlab data)

Objective: Extend the linear time invariant modelling to parametric model which parameters can be tuning variables in the MDO process.

> **Input:**

- A collection of linear dynamical model description denoted $\mathbf{H}_i$, linking n_u inputs to n_y outputs, given as
  - A linear state-space model (first or second order differential equations)
  - A transfer function (rational)
- A reduction order r (scalar)
- A p parameter grid (vector)

Output:

- A n_u inputs to n_y outputs reduced order rational p parametric model $\hat{\mathbf{H}}$

Parameter varying reduced order model (Matlab data)

Objective: Extend the parametric model with parametric and varying models, extending the viability of the model.

Input:

- A collection of linear dynamical model description denoted $\mathbf{H}_i$, linking n_u inputs to n_y outputs, given as
  - A linear state-space model (first or second order differential equations)
  - A transfer function (rational)
- A reduction order r (scalar)
- A p parameter grid (vector)
- A p parameter variation velocity grid (vector)

Output:

- A n_u inputs to n_y outputs reduced order rational p-varying parametric model $\hat{\mathbf{H}}$

Model integration (Matlab/Simulink/CPACS data)

Objective: Integrate the above full or reduced blocks in the MDO and CPACS tool chain.

Input:

- A linear dynamical model description denoted $\mathbf{H}$, linking n_u inputs to n_y outputs, given as matrices
  - `Mhh.mat`, `Khh.mat`, `Bhh.mat` and `Qhh.mat` in the second order case or
  - `A.mat`, `B.mat`, `C.mat` and `D.mat` in the first order case.
- Additional data - Drag polar
- Additional data - fixed: actuator/sensor dynamics, wind gust models

Output:

- Optimization variables
- LTI or LPV models, `.mat` files obtained in the above tasks (Matlab/Simulink data)
- Nonlinear simulation models for control for load analysis, for mission simulation (Simulink data).

3.5 Control (2.2)

Flight qualities using INDI and/or scheduled PID (Matlab data)

Objective: Design an active feedback flight control law.

Input:

- Non linear state-space model

- Controller order guess (scalar)
- Higher order analysis model?

Output:

- Controller gains
- Inversed dynamic system

GLA control using LTI/LPV $\mathcal{H}_\infty$ or Modal control (Matlab data)

Objective: Design an active feedback gust load alleviation control law.

Input:

- Linear state space models $\mathbf{H}_i$ or parameter(-varying) dependent $\mathbf{H}$, linking n_u inputs to n_y outputs,
  - Reduced order
  - LTI or pLTI or LPV
  - Input signals: disturbance (e.g. gust) and actuator commands
  - Output signals: performance (e.g. load channels) and sensor signals
  - Scaled inputs and outputs
  - Possibly including already linearised flight control system
- Weightings to balance
  - Individual performance channels
  - Robustness requirements
  - Control effort

Output:

- Controller in state-space form
- Achieved performance (e.g. closed-loop $\mathcal{H}_\infty$-norm)

MLA control using MPC approach (Matlab data)

Objective: Design an active feedback maneuver load alleviation control law.

Input:

- Linear state space models $\mathbf{H}_i$ or parameter(-varying) dependent $\mathbf{H}$, linking n_u inputs to n_y outputs,
    - Reduced order
    - LTI or pLTI or LPV
    - Input signals: disturbance (e.g. pilot stick) and actuator commands
    - Output signals: performance (e.g. load channels) and sensor signals
    - Scaled inputs and outputs
    - Possibly including already linearised flight control system
- Weightings to balance
    - Individual performance channels
    - Robustness requirements
    - Control effort

Output:

- Controller in state-space form
- Achieved performance

Flutter control using LTI/LPV $\mathcal{H}_\infty$ or modal control (Matlab data)

Objective: Design an active feedback flutter control law.

Input:

- Linear state space models

  - Reduced order
  - LTI or pLTI or LPV
  - Input signals: disturbance (e.g. gust, aerodynamical disturbances) and actuator commands
  - Output signals: performance (e.g. load channels) and sensor signals
  - Scaled inputs and outputs
- Weightings to balance
  - Individual flutter modes
  - Robustness requirements
  - Control effort

Output:

- Controller in state space form
- Achieved performance (closed-loop pole locations)

Actuator and sensor placement (Matlab data)

Objective: Optimisation of the senors and actuators use and placement. This may be used for either monitoring r closed-loop.

Input:

- Linear state space models
  - LTI or pLTI or LPV
  - Input signals: disturbance (e.g. gust) and all possible actuators
  - Output signals: performance (e.g. load channels) and all possible sensors
  - Scaled inputs and outputs
- Objective
  - Modes to be controlled / not controlled

  - Closed-loop requirements
- Limitations
  - Max. number of actuators / sensors
  - Min. observability / controllability
  - Spatial constraints w.r.t. actuator/sensor placement (e.g. no overlapping flaps)

Output:

- Optimal set of selected actuators and sensors
- Evaluated objective
- Observability / controllability-oriented measures

Control allocation for load alleviation (Matlab data)

Objective: Optimise the way actuators are used to apply a desired moment/force.

Input:

- Model LTI or pLTI or LPV
- Control law with virtual control variables as output
- Actuator limitations
- Weightings to balance
  - Control effort
  - Secondary objectives (loads, etc.)
  - Slack variable

Output:

- Control allocation system

3.6 Analysis (2.3)

Performance assessment (Matlab/Simulink data)

Objective: Evaluate control functions performances using control-oriented metrics.

> **Input:**
>
> - Open-/closed-Loop Aircraft model with nonlinearities extracted being given as a complex model in Matlab or Simulink
>
> **Output:**
>
> - Estimated performances that may be used in the MO optimisation loop

Hardware in the loop (Matlab data)

Objective: Evaluate the impact of the hardware in the performances.

> **Input:**
>
> - Open-/closed-Loop Aircraft model with nonlinearities extracted from a complex model in Matlab or Simulink
> - Open-/closed-Loop Aircraft model with nonlinearities extracted as an LFT
> - A (mathematical) description of the hardware or a Hardaware to interconnect
>
> **Output:**
>
> - Estimated performance

Worst case analysis (Matlab data)

Objective: evaluate worst case configurations, to loop the MDO process and provide assessments and or re-tuning configurations.

> **Input:**
>
> - Open-/closed-Loop Aircraft model with nonlinearities extracted from a complex model in Matlab or Simulink
> - Open-/closed-Loop Aircraft model with nonlinearities extracted as an LFT
>
> **Output:**
>
> - Estimated performance

Actuator limits (Matlab data)

Objective: evaluate the impact of the actuuator limitations in the performances (saturation in position, velocity...).

> **Input:**
>
> - Open-/closed-Loop Aircraft model with nonlinearities extracted from a complex model in Matlab or Simulink
> - Open-/closed-Loop Aircraft model with nonlinearities extracted as an LFT
> - Actuator accurate model and or limitations set
>
> **Output:**
>
> - Estimated performance

$\mathcal{H}_\infty$ norm computation for large-scale and delayed models (Matlab data)

Objective: Evaluate worst case frequency response in a very large scale context.

> **Input:**
>
> - A linear dynamical model description denoted $\mathbf{H}$, linking n_u inputs to n_y outputs, given as
>   - A state-space model (first or second order)
>   - A transfer function (rational or irrational)
>
> **Output:**
>
> - Estimated $\mathcal{H}_\infty$-norm.

4 Conclusions

This brief reports tries to present the overall control system layout. it mainly presents a road map for this WP2 and a - quite - detailed task sharing. No specific schedule is provided here but preliminary results in modelling are expected in beginning 2021.

Of course, interaction with flight test should also be considered, but at the present stage of the project, these later remains quite out of the considerations within this work package.

To end this section, the following publications within FLiPASED, should be mentioned

- D. Ossmann, T. Luspay and B. Vanek
  "Baseline Flight Control System Design for an Unmanned Flutter Demonstrator"
  in Proceedings of the IEEE Aerospace Conference, Big Sky, MT, USA, 2019.
- B. Takarics, B. Patartics, T. Luspay, P. Bauer and B. Vanek
  "Active Flutter Mitigation Testing on the FLEXOP Demonstrator Aircraft"
  in Proceedings of the AIAA SciTech Forum, Orlando, Florida, 2020