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AN ENERGETIC APPROACH TO AEROELASTIC ROTORCRAFT-PILOT COUPLINGS ANALYSIS

Georges Tod, François Malburet, Julien Gomand, Pierre-Jean Barre and Benjamin Boudon

georges.tod@ensam.eu, francois.malburet@ensam.eu, julien.gomand@ensam.eu

Arts et Metiers Paristech, Aix-en-Provence, France

Abstract

This paper describes an energetic method using multibond graphs to model multi-physical systems. Its potential in building physical meaningful graphs that represent equivalent mathematical models of classic analytical approaches is shown. An application to the study of an aeroelastic rotorcraft-pilot coupling is studied by analyzing the passive pilot behavior in the cyclic control loop. A rotorcraft in hover flight is simulated and perturbed on its rolling motion axis. Depending on the rotorcraft characteristics air resonance may occur, and the pilot may involuntarily excite the cyclic lever, increasing the rolling motion of the fuselage to an unstable point. Future work will explore eventual alternative solutions to notch filters to avoid passive pilot reinjection at low fuselage frequency modes by controlling for example the actuators of the swashplate through model inversion using the bond graph method.

NOTATIONS

AR	Air Resonance
RPC	Rotorcraft Pilot Coupling
MBG	Multibond Graph
FCS	Flight Control System
DoFs	Degrees of Freedom
DAEs	Differential Algebraic Equations
z	Rotorcraft altitude
m_f	Fuselage mass
b	Number of rotor blades
$F_{Lift\ i}$	Lift force provided by blade i
k_{FCS}	Constant gain of the FCS
θ_c	Collective pitch
k_{aero}	Time invariant aerodynamic coefficient

Multibond graph elements are expressed in three dimensions: power arrows transport one flow and one effort three dimensional vector.

1	Common flow junction
0	Common effort junction
R	Damper
C	Spring
MSe	Ideal modulated source of effort
MTF	Modulated power conservative matrix
MTX	Cross product matrix
MTA	Rotation matrix

1. INTRODUCTION

Rotorcraft dynamics are complex to analyze not only because a large number of subsystems can dynamically interact but also from the multiplicity of physical domains they imply. Since, no matter the physical domain, all the subsystems exchange energy, a different path to building equivalent mathematical models of a physical system than with analytical approaches is to independently model bond graphs of each subsystem and then connect them together with power bonds.

To illustrate this potential, the dynamic behavior of a helicopter prone to Air Resonance (AR) during an aeroelastic Rotorcraft-Pilot Coupling (RPC) event is studied. Concerning AR, the interaction between blade lead lag motions and fuselage pitch and roll motions have been deeply investigated with analytical models such as described by Takahashi and Friedmann in [1] or more recently with a minimalistic number of degrees of freedom by Krysinski and Malburet in [2]. In a recent effort to improve the understanding of the interaction between pilot and aircrafts/rotorcrafts, European research groups such as GARTEUR and ARISTOTEL have led research on rotorcraft pilot couplings. In 2008, the GARTEUR group [3] classified aeroelastic RPCs as phenomena concerning the 'passive' behavior of the pilot subjected to cabin vibrations of a frequency range between 2 and 8 Hz. Since this range contains the fuselage roll and pitch modes frequencies, one can easily imagine, that at these relatively high frequencies for the pilot, he may not be physically able to control his feedback into the cyclic lever. The result is an involuntary injection of in-plane efforts in the rotor that excite into the non-rotating frame the fuselage; many examples can be found in Walden's

extensive US Navy and Marine Corps retrospective [4]; as shown by Walden, this phenomenon concerns not only classic helicopters but also more unconventional aircraft architectures like the V-22 Osprey; and since VTOL technologies tend to more unconventional architectures like Sikorsky's X2, Eurocopter's X³ and Bell/Agusta's BA609 with lighter and more flexible aircrafts, their proneness to aeroelastic phenomena will still be an area of interest.

Concerning, the passive pilot reinjection, Mayo proposed in [5] a famous transfer function to model the pilot's biodynamics in the collective control loop. More recently, in [6], Venrooij and al. showed that the highest levels of biodynamic feedthrough are measured in lateral directions. In the present study, RPCs involving these lateral directions are investigated by modeling the interactions of right pilot's arm and the cyclic control lever. During a hover flight maintained by the FCS; at a given time, a wind gust is simulated that disturbs the fuselage on its roll axis. Both rotorcraft and pilot models are developed using a multibody approach. An equivalent approach has been proposed by Mataboni et al. [7]. The rotorcraft multibody model is based on Chikhaoui et al.'s work [8]. The energetic method used in this paper is based on bond graphs; Paynter [9] imagined them in the late 50's and extensive work has been then carried out by Margolis and Karnopp [10]. In the aerospace industry, Granda and Montgomery have shown the potential of scalar bond graphs in building space state systems [11] in application to the analysis of the dynamics of the International Space Station [12]. In this paper, the extension of scalar to vector bond graphs, so called multibond graphs will be used. Actually, they are more adapted to the modeling of multibody mechanical systems undergoing large spatial motions.

The objectives of this paper are, firstly to focus on the energetic method to couple subsystems, which can be multi physical; and show its potential, more than developing new knowledge models. On the second part, it details a model to simulate an aeroelastic RPC event through the cyclic controls in hover flight.

One of the perspectives in the use of multibond graphs (MBG) is to be able to graphically design by model inversion a controller to actively control for example the swashplate actuators and alleviate aeroelastic RPCs.

2. ENERGETIC APPROACH

Basically, in energetic approaches, like bond graphs, one builds a graph in which elements exchange power through multiport junctions; extensive explanations can be found in [13]. The multi physical characteristic of bond graphs is based on analogies on efforts and flows see table 1. In mechanics, each power bond transports an effort that can be a force or an angular moment and a flow that can be a velocity or an angular velocity; power is obtained on each bond by the dot product of the effort vector and the flow

vector. Equivalent mathematical models to classic analytical methods can be obtained (figure 1) by assembling predefined bond graph architectures.

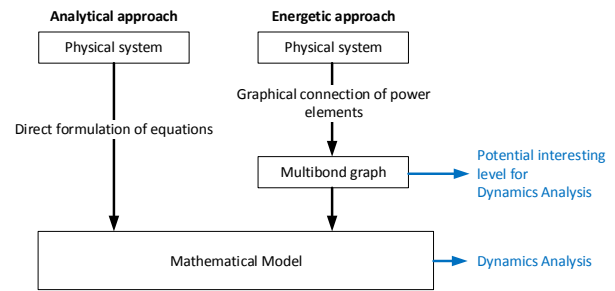


Figure 1. The energetic approach

In the case of multibody systems, Tiernego and Bos [14] described the multibond graph architecture of a rigid body, see figure 2a. The architecture they proposed is based on Newton-Euler's equations of motion. The movements of the bodies are classically constrained with joints; the architectures of revolute and spherical joints taking into account some flexibility have been detailed by Zeid in [15] and are presented in figure 2b. It can be noticed there is no difference between flexible revolute and spherical joints bond graph architectures; the constraint of degrees of freedom is expressed with a set of springs and dampers. In terms of bond graphs, the two joints are distinguished with the characteristic values of R and C elements.

To obtain the bond graph of the multibody system, the rigid bodies' graphs are connected to the joints' graphs. Once this is set, MTF elements need to be parameterized with geometrical data and the rotation matrices according to desired rotational and translational velocity fields; one does not need to think about the internal efforts between bodies. Finally, eventual external efforts are connected to the graph. The example of the fuselage rigid body can be found in appendix 1.

Table 1. Multiphysics in bond graphs [13]

<i>Energy domain</i>	<i>Effort</i>	<i>Flow</i>
Translational mechanics	Force	Velocity
Rotational mechanics	Angular moment	Angular velocity
Electro-Magnetic domain	Voltage Magnetomotive force	Current Magnetic flux rate
Hydraulics	Total pressure	Volume flow
Thermo dynamic	Temperature	Entropy flow

In order, to illustrate the potential in the vision given by multibond graph representations, a simplified macroscopic symbol of rigid bodies and joints MBG architectures are proposed in figures 2c and 2d. In the macroscopic symbols, the vertices of each figure represent a 0 or 1 bond graph junctions which are the spots where external power can be exchanged.

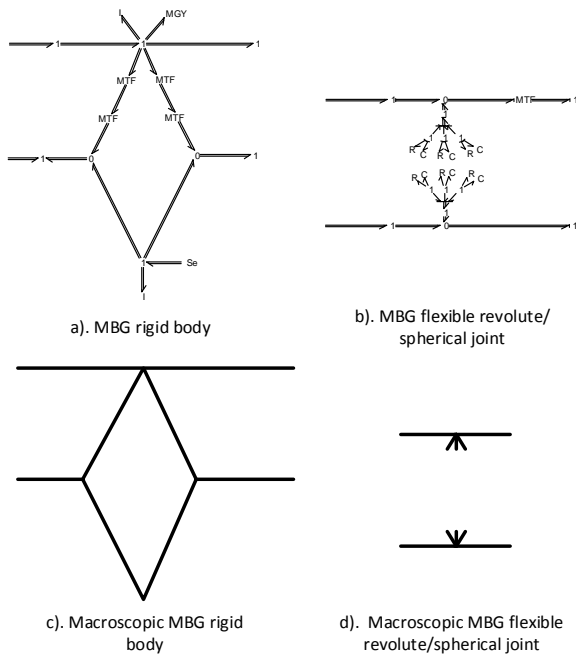


Figure 2. Multibond graphs of a rigid body and a flexible joint and their simplified macroscopic symbols

Now, let us consider the multibody model that will be necessary to study the RPC event presented in the next section, see figure 3. The pilot's shoulders are supposed to be attached to the fuselage through flexible joints on one side; on the other side they are linked to the collective and cyclic pitch levers. These inceptors are as well, linked to the fuselage through flexible joints.

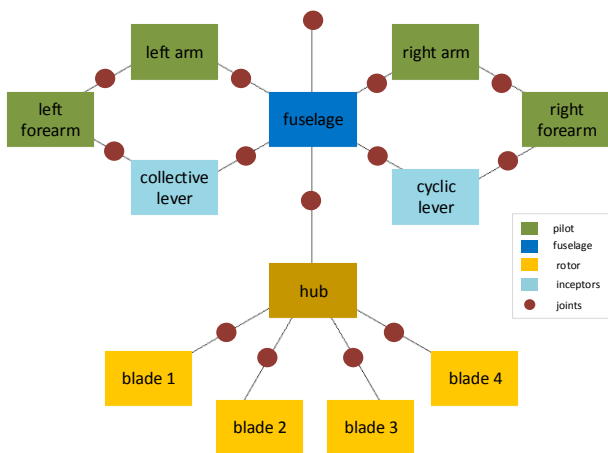


Figure 3. Pilot-Fuselage-Rotor multibody model

By representing the macroscopic symbols presented in figure 2 under each rigid body and joint, the whole model multibond graph topology can be obtained in figure 4. As a remainder, between each vertices of the resulting figure, power circulates. Many non-obvious power cycles appear and will be analyzed in future work; they will eventually allow analyzing the dynamics of the system without having to run a time simulation.

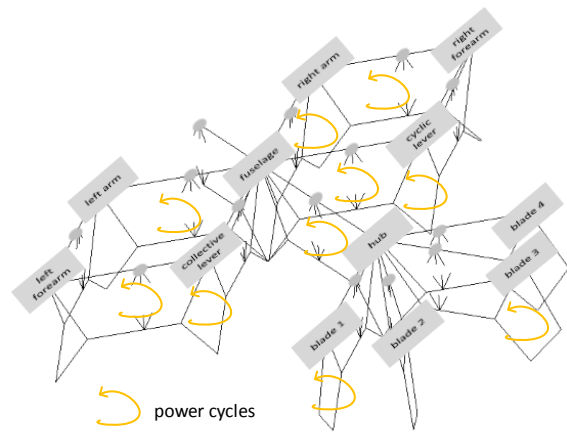


Figure 4. Power cycles to be graphically analyzed

Another interesting feature of energetic approaches is their modularity: each subsystem can be modeled independently and then plugged together at one of the vertices of a more complex model. For example, figure 5, shows the left arm, left forearm of the pilot and the collective lever modeled and simulated offline before being plugged into the complete model. As a result, the degree of detail and complexity of a model can be gradually increased.

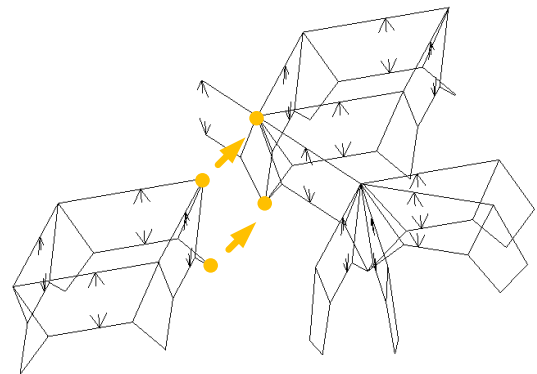


Figure 5. Power plugging models

3. APPLICATION TO AN AEROELASTIC RPC

In this section, an energetic model to simulate the pilot-fuselage-rotor interactions is proposed. The method has been defined in the previous section and figure 3 shows the rigid bodies and flexible joints that are taken into account in the following study. Concerning the flight controls, the actuators are supposed to be rigidly attached to the fuselage, see figure 6. The actuators are controlled with the cyclic lever's angle information. As a result, it is assumed in this model that the pilot that does not have a force feedback from the rotor. As a remainder, the flight configuration of present interest is a hover flight; the fuselage will be then perturbed, and the dynamic responses of the rotor, pilot and fuselage will be studied.

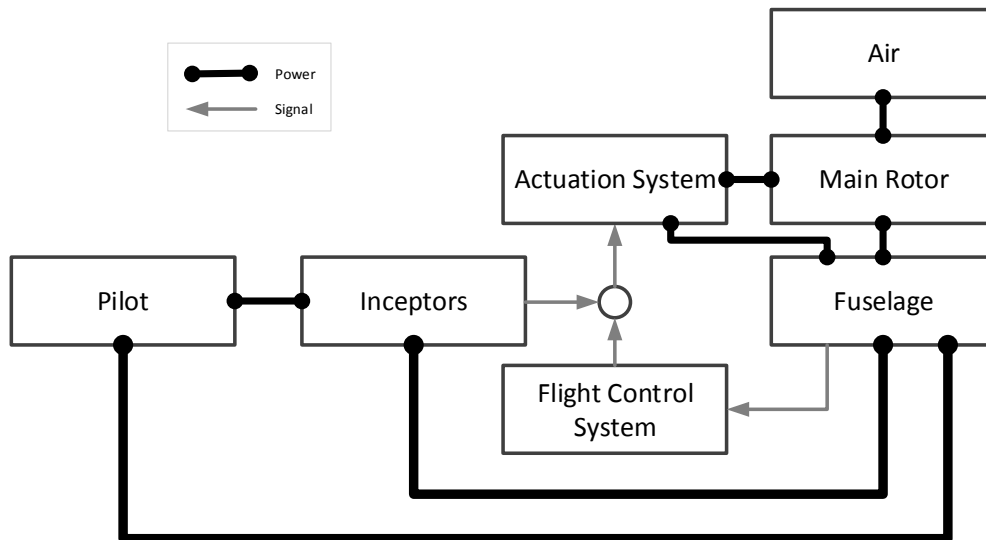


Figure 6. Pilot-Fuselage-Rotor model assumptions scheme for aeroelastic RPC simulation

3.1. Bioaeroelastic modeling of a rotorcraft and a pilot

As stated by ARISTOTEL, one of the key problems in tackling RPC for future rotorcraft designs is the lack of adapted pilot and vehicle models; the two can hardly be dissociated [16].

More research efforts have been conducted in fixed wing than in rotary wing concerning the aircraft and pilot interactions. In [17], Lone and Cook propose an extensive review of the pilot modeling techniques. They describe three main categories when it comes to pilot modeling: the human sensory models, the human control theoretic models and the human body models. Our study, concentrates on the last category, and concerns the biomechanical modeling of the two arms of the pilot.

Pilot's passive biodynamics

The arms of the pilot are decomposed into two rigid bodies: forearm and arm. Shoulder, elbow and wrist articulations are considered as flexible joints, see figure 7. The biological characteristics were obtained from literature, see table 2.

Table 2. Pilot's arm data

	Inertia(kg.m ²)	Mass (kg)	Data source
Arms	0,012	1,372	STI, [18]
Forearms	0,015	1,017	
	Stiffness (Nm/rad)	Damping (Nms/rad)	Data source
Shoulder	4	0,04	POLIMI, [7]
Elbow	3,5	0,035	
Wrist	99,1	0,991	

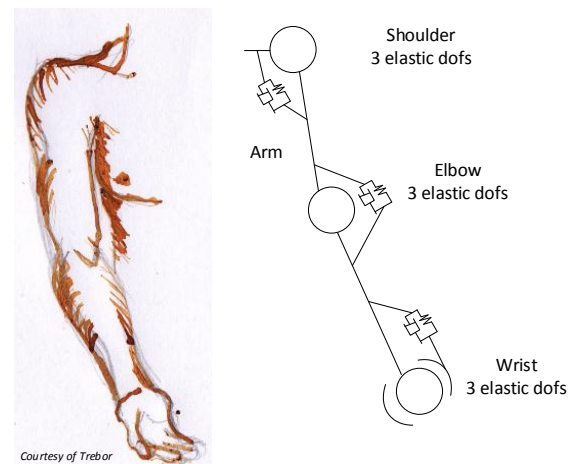


Figure 7. Biomechanical model of the pilot's right arm

When compared to biomechanical pilot transfer function models, like discussed in the introduction, multibody pilot models have the advantage to be more easily adaptable to a specific aircraft cockpit, see figure 8. Therefore, new rotorcraft designers could evaluate the impact of their cockpit designs in terms of RPCs while the cockpit geometry is being defined during the pre-design process. Whereas studying collective bounce, this has probably a reduced impact, since movements are only vertical; it may not, when studying the cyclic control loop. The distance between the elbow of the right arm of the pilot and the aircraft symmetry plane has an effect on the gain between the roll angular acceleration of the fuselage and the tangential effort the pilot introduces in the cyclic lever.

The inceptors are modeled following the same logic: collective and cyclic levers are considered as rigid bodies attached to the fuselage through flexible joints.

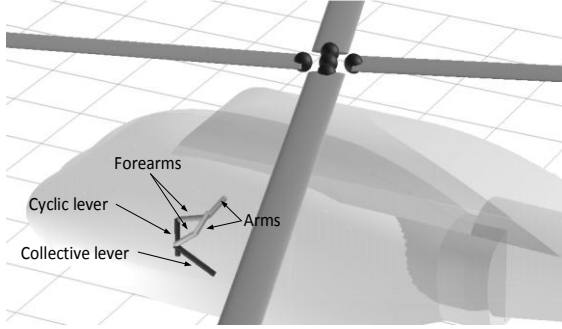


Figure 8. Positioning of the pilot in the cabin

Aeroelastic rotorcraft and rotor actuation system

The rotorcraft model is based on Chikhaoui et al.'s work [8] with an extra DoF, the altitude of the fuselage and an original bond graph architecture of the joints between the blades and the rotor hub presented in [19]. The blades are considered rigid and articulated in pitch, flap and elastic lag; this last choice will let the possibility to see the impact of the pilot on the damping of the first lead lag mode. The fuselage can translate in x,y,z directions and rotate around pitch and roll axis. The yaw angular motion is blocked. Basic aerodynamic lift forces are included using the blade element theory.

Flight mechanics and FCS

In the present study, the rotorcraft needs to be trimmed in hover. The role of the FCS introduced in the system is to keep the altitude constant by controlling the collective pitch of the aircraft. At the beginning of the simulation, the initial collective pitch angle is set to compensate for the fuselage weight. However, during the simulation we will disturb the system on the roll axis of the aircraft generating an oscillation of the altitude; since the rotorcraft is already close to a steady state position, we can approximate the aerodynamic lift forces per blade and the dynamic equilibrium of the fuselage,

$$\text{with, } F_{Lift_i} = \frac{k_{aero}}{b} \cdot \theta_c \quad \text{and, } m_f \cdot \ddot{z} = -m_f \cdot g + \sum_i^b F_{Lift_i}$$

$$\text{as a result, } m_f \cdot \ddot{z} = -m_f \cdot g + k_{aero} \cdot \theta_c .$$

Therefore, by sending a collective pitch signal equal to $k_{FCS} \frac{m_f \cdot \ddot{z}}{k_{aero}}$ we can reach the vertical static equilibrium we were looking for.

Mathematical model integration and simulation conditions

Concerning the integration of the mathematical model, the usual simulation issues and constraints have to be overpassed. The first one concerns the mathematical model of the pilot's arms and levers: these models contain kinematic loops that lead to Differential Algebraic

Equations (DAEs) that are solved using the singularly perturbed formulation for bond graphs proposed by Zeid [20].

To keep a smooth numerical continuity, the degrees of freedom of the fuselage are released one after the other at the beginning of the simulation. The energy provided by gravity and the engine are also gradually introduced in the model.

3.2. Results

The simulated flight configuration is a hover flight; the rotorcraft weights 8 tons and equipped with a 4 bladed soft-in-plane rotor. At $t=20s$ after the beginning of the simulation, a torque step representing a wind gust perturbs the fuselage on its roll axis and the system's dynamic response is observed.

The chosen baseline scenario is characterized by a cyclic lever's stiffness equal to $k=625 \text{ Nm/rad}$ and damping $c=3 \text{ Nms/rad}$. The first simulation shows the pilot's feedback in the cyclic control loop, see figures 9 and 10. The pilot's right arm plus inceptor and fuselage natural frequency responses are around 3Hz. The cyclic lever oscillates between $\pm 1^\circ$, which correspond to lever's top extremity displacements of $\pm 8 \text{ mm}$. The fuselage oscillations are between $\pm 0.3^\circ$. Figure 10 shows that with the pilot in the loop the roll motion of the aircraft is less damped and the result is an aeroelastic RPC event.

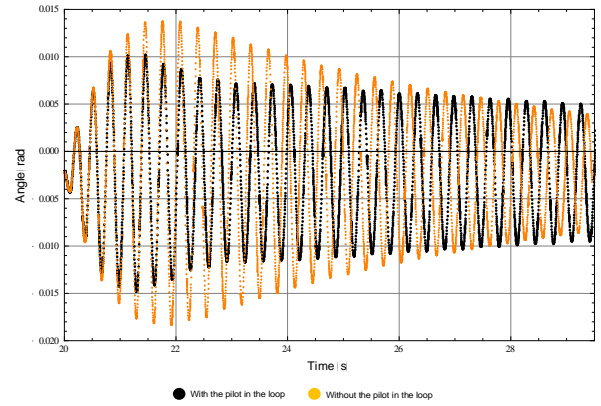


Figure 9. Cyclic lever roll angle

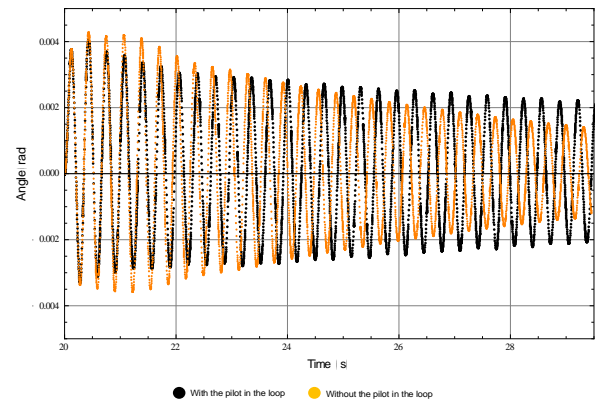


Figure 10. Fuselage roll angle

Limiting the pilot's feedback in the cyclic control loop

From the baseline case scenario defined before, some influent parameters are modified and their impact on the stabilization of the roll motion of the aircraft is quantified. In order to visually evaluate the impact of each parameter, one can evaluate how fast the roll motion of the aircraft is damped by looking at the phase portraits presented in figures 12 to 16. All the obtained phase portraits are spiral sinks (fig. 11) and are obtained during the 10 seconds following the impact of the wind gust on the fuselage. Figures 13 to 16 have to be compared to the baseline scenario phase portrait presented in figure 12. The faster the spiral converges towards the origin of the plot, the more the motion is damped: figure 15, shows the worst case scenario, when the additional 30% of stiffness on the cyclic lever baseline lowers the damping of the fuselage roll motion to almost zero. On the other side, by decreasing by 10% the cyclic lever stiffness baseline, the trajectory seems attracted to the origin much more quickly than any other cases, meaning the energy brought by the disturbance to the system is relatively quickly dissipated.

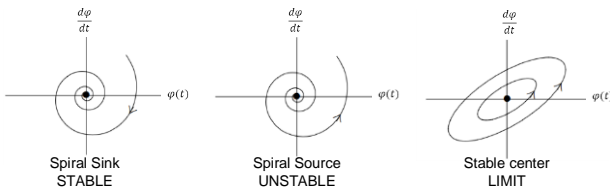


Figure 11. Fuselage roll trajectory in the phase plane

The cyclic lever gain parameter is the amplitude of the kinematic relation between the cyclic lever angular position and the blades cyclic pitch. Even if this parameter has its importance, lowering it decreases the handling qualities of the aircraft. Another important parameter is the damping of the lead-lag regressive mode by lag dampers - figure 14. Increasing their characteristics may alleviate aeroelastic RPCs occurrences. Since lag dampers characteristics are defined during pre-design phases, the proposed MBG rotorcraft and pilot's arms biomechanical model could be useful to alleviate such phenomena in an early design phase.

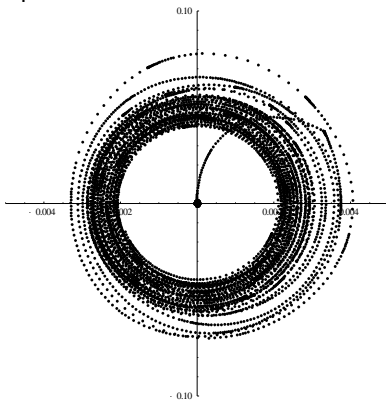


Figure 12. Fuselage roll angular velocity/angle (baseline)

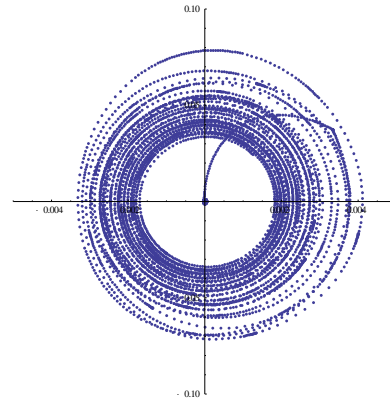


Figure 13. Fuselage roll angular velocity/angle (baseline -20% cyclic lever gain)

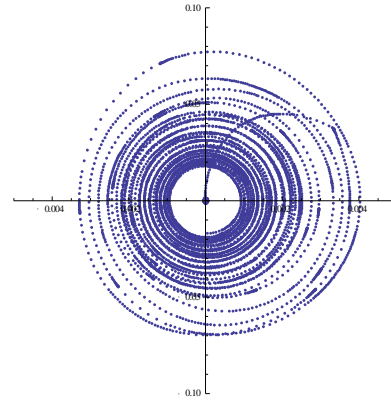


Figure 14. Fuselage roll angular velocity/angle (baseline +30% damping and stiffness on blades lag DoFs)

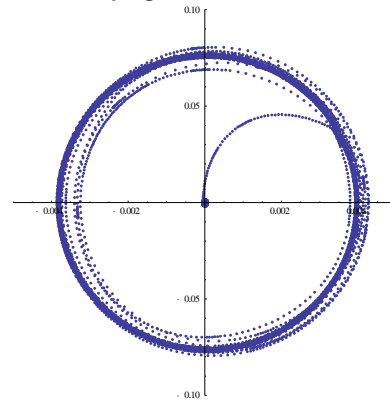


Figure 15. Fuselage roll angular velocity/angle (baseline +30% cyclic lever stiffness)

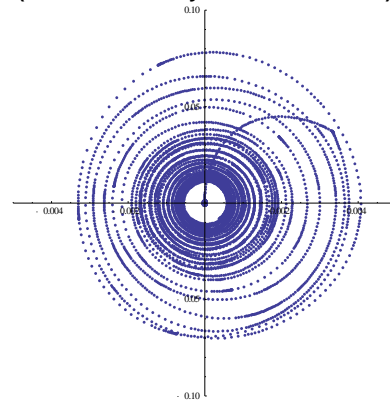


Figure 16. Fuselage roll angular velocity/angle (baseline -10% cyclic lever stiffness)

Energetic methods allow obtaining equivalent mathematical models to those obtained with classical analytical methods. Their potential in increasing the level of detail of a model by integrating new subsystems has been illustrated. These subsystems can be modeled, tested and validated independently before being power plugged into the global multibond graph of a physical system. In our case, we could imagine the complexification of the presented aeroelastic model by integrating literature's energetic submodels such as the main rotor's suspension [21] and the flight controls [22],[23].

A projection of a dynamic multibody system in the space of multibond graphs was proposed; this vision reveals the presence of power cycles that will be analyzed to

The method was applied to study an aeroelastic RPC, in which the pilot acts in the cyclic control loop of a helicopter during hover flight perturbed by a wind gust on its rolling axis. It will be interesting in the future to cross the simulation results with experimental results and explore the impact of the pilot in the whole flight envelop. The future pilot's models could include the neuromuscular system of the pilot's arms. Apart from the originality of the method, future work will also explore alternative solutions to notch filters to avoid passive pilot reinjection at low fuselage frequency modes by for example controlling the actuators of the swashplate through model inversion using the bond graph method.

The diagram illustrates the Kalman filter architecture for a quadcopter, showing the flow of information between various components:

- Gyro**: Measures body angular velocity in the body frame.
- MTX**: Measures acceleration in the body frame.
- MTA**: Measures gyro bias.
- I MSe**: Integrated motion error.
- Rotation Matrix**: Converts body frame measurements to the inertial reference frame.
- Center of gravity velocity in the inertial reference frame**: The target state for the filter.

The diagram is color-coded to represent different reference frames and types of data:

- Purple**: Body angular velocity in the body frame.
- Green**: Center of gravity velocity in the inertial reference frame.
- Black**: Other components and measurements.

Arrows indicate the flow of data and the influence of process noise ($coeff_p$) on the integrated motion error.

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