# On the influence of airframe flexibility on rotorcraft pilot couplings

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**Abstract.** A set of numerical simulations of the interactional dynamics of the pilot-rotorcraft system is performed. The aim of the numerical analysis is to evaluate the stability of the closed-loop system in hovering conditions, focusing on the influence of the first airframe flexible mode, the one with the most participation in relative motion between the main rotor and the pilot's seat and closest in frequency to pilot-vehicle interaction. Two approaches are employed. First, a linear analysis, in which the modal representation of the airframe flexible mode is added to a linearized model of the helicopter vertical motion and the helicopter dynamics is coupled with a single degree of freedom linearized model of the pilot biomechanics. Subsequently, a multibody model of the helicopter is coupled with the same linear model of the pilot, trimmed in hover and perturbed by a vertical gust. A sensitivity analysis shows that such mode has a significant influence on the stability of the closed loop system, especially if its frequency is close to the natural frequency of the pilot's biomechanics, as one might expect.

## Introduction

The interaction between pilot and vehicle dynamics represents a challenging issue for rotorcraft. Rotorcraft-Pilot-Couplings (RPC) can be at the root of different kinds of unwanted, adverse feedback loops: PIO (Pilot-Induced Oscillations) and PAO (Pilot-Assisted Oscillations). The latter, the object of this research, are characterized by the involuntary participation of the pilot. Human-machine coupling can be described by a feedback loop that connects the rotorcraft and the pilot. While aeroelastic effects on PAOs due to structural flexibility have been the subject of previous research [1], also addressing tiltrotor aeroelasticity [2], no extensive sensitivity analysis has been performed so far. This work aims at filling this gap through a numerical investigation.

## Problem description

The goal of this work is to perform a closed loop stability analysis for the coupled rotorcraft-pilot system. For both parts of this work the pilot is described by a state space representation of the BDFT (Biodynamic feedthrough). The BDFT is defined as the transfer function between the control inceptor rotation and the airframe acceleration input. The pilot model is coupled with another state space system that describes the helicopter dynamics. The vertical acceleration of the airframe is fed through the pilot biomechanics to the collective control deflection, which in turn produces a vertical acceleration of the airframe.

## Methods

The work has been divided into two parts. In the first part, the analysis is performed using Linear Time Invariant (LTI) models. To represent the selected rotorcraft, a simple analytical model consisting of the helicopter heave motion and the main rotor coning motion as proposed in [3] has been used, considering data representative of a light helicopter of the class of the BO105. Modal data available from previous work supports the modal representation of an analytical model including the dynamics of the airframe. A sensitivity analysis has been performed, changing the frequency of the first airframe flexible mode, the one closest to the frequency of the pilot's biomechanics and the most involved in the relative vertical motion between the main rotor mast and the pilot' seat, to understand how this parameter can affect the stability of the closed loop system composed by helicopter and pilot. In the second part of this work the rotorcraft is represented through a flexible multibody model, implemented in the free, general-purpose multibody solver MBDyn. The results are used to investigate how well such a simple analytical model can predict the results obtained from a full flexible multibody model.

## Analytical model

### Elastic airframe addition

The analytical airframe representation proposed in [3] has been enhanced by adding airframe flexibility, described using a modal model obtained from a finite element analysis. The first four mode frequencies are listed in Table 1.

*Table 1: Airframe modes*

| **Mode** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|
| **Frequency [Hz]** | 5.8 | 7.7 | 11.4 | 12.6 |

The first and the third modes present the most participation of hub and pilot seat vertical relative displacement. It is worth noticing that the third mode is outside the frequency range typical of PAO events (3-7 Hz): t*herefore, only the effect of the first mode is analyzed in detail.*

### Closed loop sensitivity analysis

The loop transfer function of the pilot-vehicle system can be written as:

$$H_{LTF}(s) = -G\, H_{BDFT}(s) H_{HELI}(s)$$

*Equation 1*

where *G* is the gear ratio between the collective inceptor deflection and blade pitch, $H_{HELI}(s)$ is the transfer function between the collective pitch and the pilot seat vertical acceleration.

Figure 1 shows how the 1st airframe mode (at 5.8 Hz) affects the loop transfer function.

After adding the airframe elasticity, a sensitivity analysis has been performed moving the 1st mode frequency in the range [f ± 40%]. The gain and phase margins on the system's closed-loop transfer function have been chosen as indices to evaluate the system's stability.

The sensitivity analysis results are presented in Figure 2. The mode frequency increases from red to blue. The gain margin rises when the mode frequency increases. When the frequency is set to the lower end the gain margin is negative, therefore the system is unstable. Moving towards the upper bound the gain margin increase shows a non-linear trend. The most significant improvements are visible up to 5.5 Hz; the value tends to settle for higher frequencies. The explanation behind this behavior is related to that of the pilot. The typical frequencies that describe the human response in these conditions are in the range [1.5 Hz–4.5 Hz]; departing from this range the mode frequency has less influence on the system's stability.

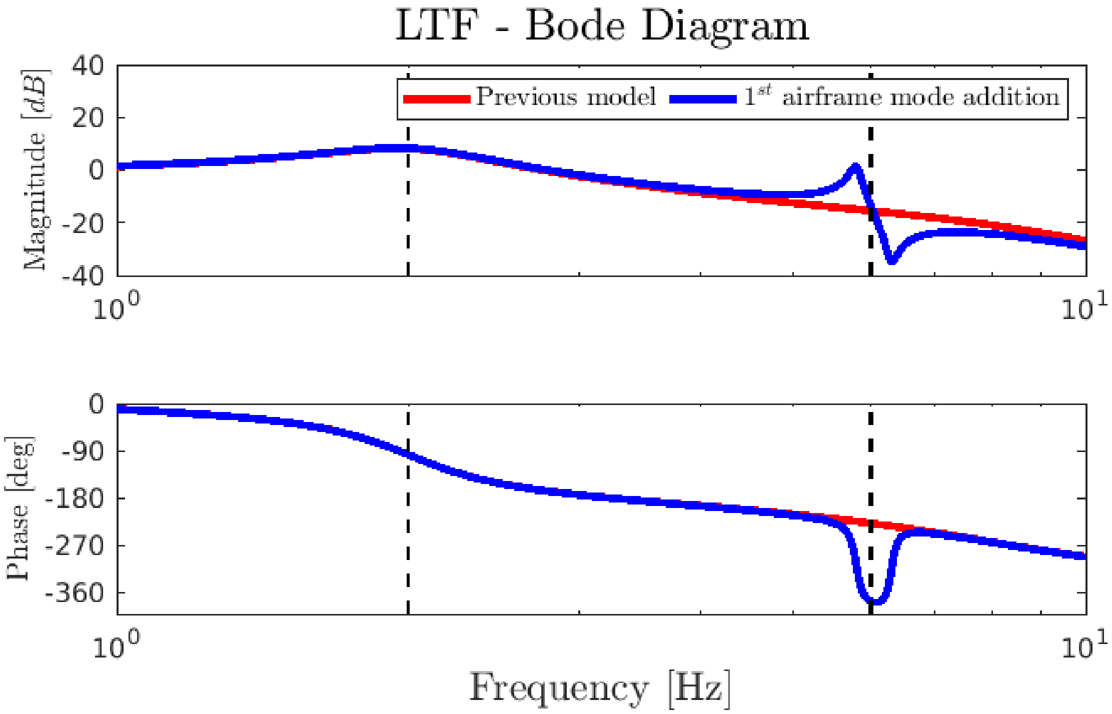

*Figure 1: Loop transfer function, with and without 1st airframe mode*

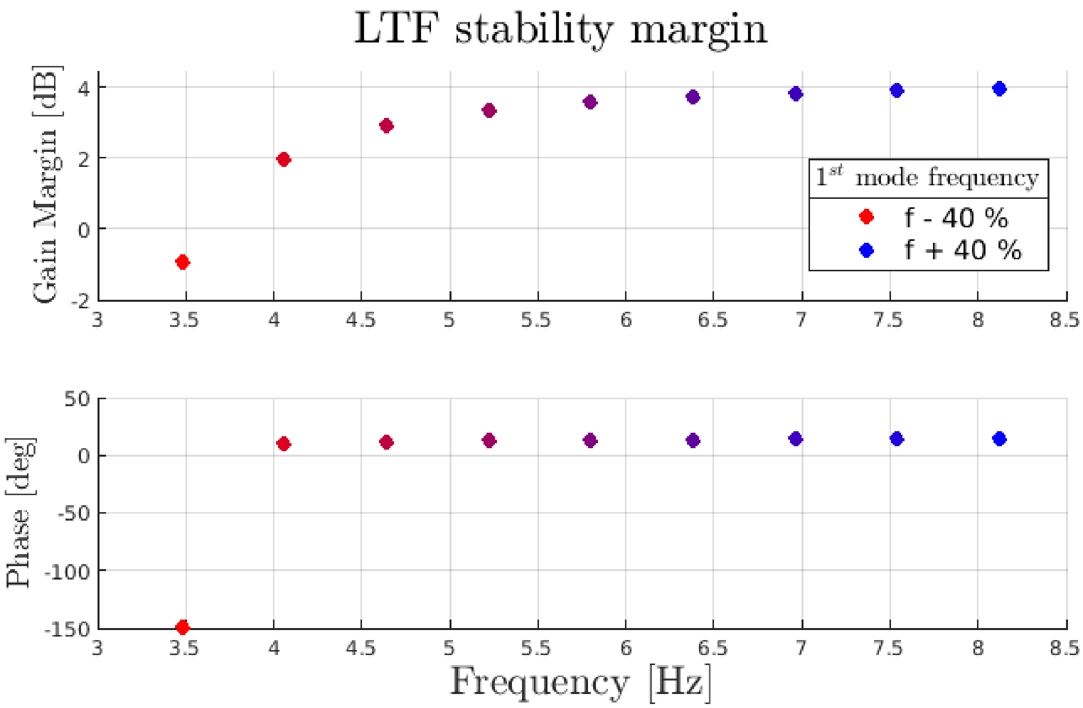

*Figure 2: LTF stability margin changing 1st mode airframe frequency*

**Multibody model**

After studying the collective bounce using a simple analytical model, a more detailed, fully flexible multibody model has been used to describe the dynamics of the helicopter.

For fairness of comparison the same pilot model is used and, as in the analytical study, only the first airframe mode has been enabled for the airframe dynamics.

The 1st airframe frequency has been moved to the value corresponding to zero gain margin. The model had been trimmed in hover, after which a perturbation in the form of a gust in the vertical direction has been introduced, after 5 seconds of simulation time, and the system's response has been evaluated. (Figure 3)

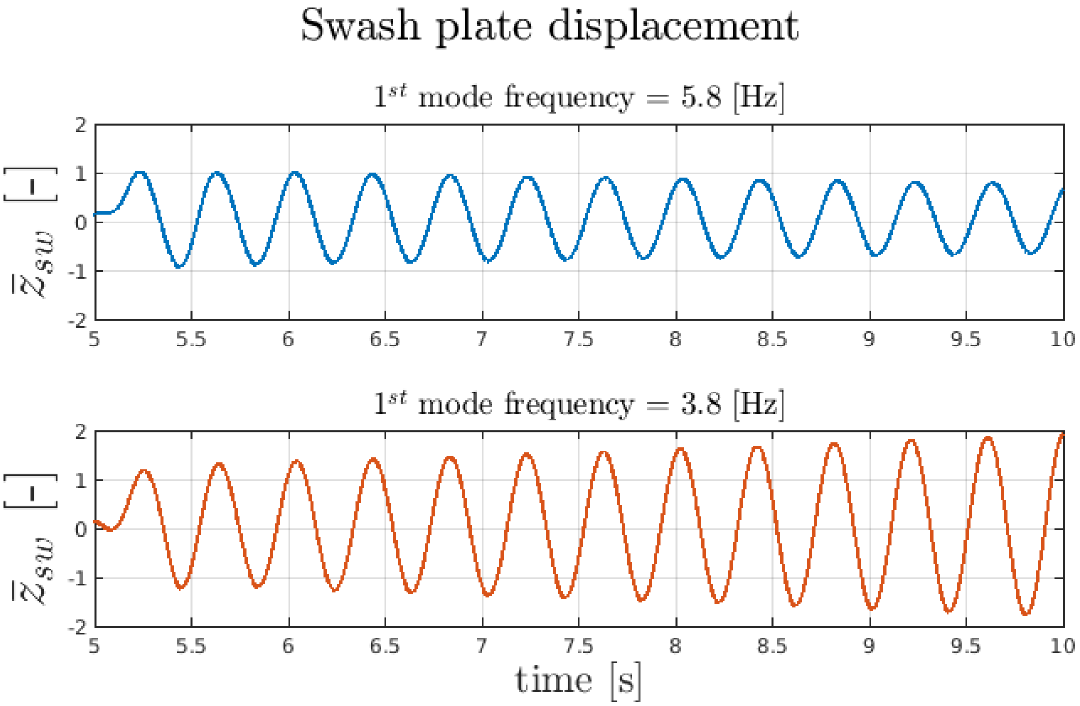

*Figure 3: Closed-loop system vertical gust response*

In Figure 3, $\bar{z}_{sw}$ (the normalized swashplate displacement with respect to its value at 5 s) is shown. After 5 seconds, the perturbation starts. When the 1st frequency is set to the nominal value listed in Table 1, the amplitude of the oscillations slowly decreases (damping $\xi = 0.005$). If the 1st airframe frequency is reduced to 3.8 Hz, i.e., the value corresponding to marginal stability in the LTI system, the system is not able to absorb the disturbance and the oscillations increase: the system is unstable (damping $\xi = -0.007$). It is worth stressing that the results in Figure 3 have been obtained increasing the pilot gain transfer function by 35%. The increased stability margin is probably due to increased damping introduced by the flexible dynamics of the system and by the nonlinearities included in the multibody simulations.

## Conclusions

This work analyzes how the airframe mode can play a key role in rotor pilot coupling. It shows that the reduction of stability margins, and the possible development of instability, is also related to the airframe elasticity. More analyses and investigations are nonetheless needed to enhance the comprehension of the phenomenon.

## References

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