Weight effects on simple adaptive shimmy suppression system: a case study

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Abstract. The problem of the shimmy oscillation of aircraft’s nose landing gear is of great interest because such vibration can carry detrimental effects. An adaptive vibration suppression system based on the Modified Simple Adaptive Control is here considered. The saturation of actuator control moment is taken into account and a simple back calculation scheme is introduced to avoid windup effects. The work investigates numerically the influence of aircraft weight on the controlled system response under different disturbing condition.

1. Introduction

Landing gears can occasionally incur in a phenomenon called shimmy vibration. It is characterized by an unstable oscillation of the wheel or boogie around the vertical or steering axis, in the case of nose landing gear NLG shimmy. The phenomenon is engendered by the tire-road interaction and manifests itself as the taxiing speed becomes greater than a critical value: what happens is that friction interaction between the pneumatic and the pavement no longer dissipate system energy but, on the contrary, it amplifies the landing gear vibrations that become self-sustained [1]. The consequences of shimmy vibrations are not negligible since, beyond the discomfort perceived in the cabin by pilots or passenger, they cause wearing of components, reduce the fatigue life of structural elements and can eventually damage the gear leading to incidents or accidents. Mitigation measures are thus mandatory to avoid or reduce the detrimental effects that the shimmy vibrations may result in. The well-established solution is represented by the use of a passive shimmy damper; attached to the NLG leg, it increases the damping capability of the system [2]. However, the main drawback is represented by the fact that the passive shimmy damper performance, maximized in the design condition, can lower in off-design condition due, for instance, by different taxiing speed, by different system weight, by the variation of tire pressure or by meteorological related pavement conditions. Alternative damping solution are thus investigated to reach a certain degree of adaptivity of the shimmy suppression system: among others semi-active [3,4], active [5,6, 7] and adaptive [8,9] control systems have been investigated by scientific community.

In this work, the response of a nose landing gear shimmy suppression system based on the Modified Simple Adaptive Control MSAC scheme is numerically studied [10, 11]. The MSAC is a simplification of the Simple Adaptive Control [12,13] which, in turn, is a modification of the Model Reference Adaptive Control MRAC. Difference between methods are the MRAC asks for a full state feedback and for a definition of a reference model of the same order of the plant while SAC and MSAC are output feedback control systems and the order of the reference model can be higher or lower than that of the plant. Both differences are advantages in terms of simplicity of the scheme and number of sensor installation. More in detail, SAC uses a feedback control signal which is a
combination of three terms proportional, through adaptive gains, to the tracking error, to model state and model input signals, respectively. Once the almost strict passivity of the system is ensured, or gained by using a Parallel Feedforward Compensator PFC, the asymptotic convergence of the output tracking error of the SAC controlled system is ensured [14]. In some particular case, for instance when the reference to be tracked is identically zero (as it is the case in the present study), the SAC can be further simplified to the MSAC which uses a feedback control signal that is only proportional, through adaptive gains, to the tracking error. In all the other cases it can not be advisable to further simplify the SAC scheme, particularly when a time varying reference is to be tracked.

2. Mathematical model

This paragraph briefly recalls the NLG governing equations along with the linearized SISO representation and MSAC controller scheme augmented with the AW to reduce the negative effects caused by the actuator saturation.

2.1 Shimmy governing equations

The problem governing equations can be written in terms of the shimmy rotation $\dot{\psi}$ and velocity $\ddot{\psi}$ and in term of the tire side-slip angle $\alpha$ in state space representation as

$$
\begin{aligned}
\frac{d}{dt}\begin{bmatrix}
\dot{\psi}(t) \\
\dot{\alpha}(t)
\end{bmatrix}
= &
\begin{bmatrix}
0 & \frac{K_E}{J} & -\frac{1}{J} \left( C_D - \frac{\kappa}{V} \right) & 0 \\
\frac{V}{\sigma} & \frac{e-a}{\sigma} & \frac{e-a}{\sigma} & \frac{V}{\sigma}
\end{bmatrix}
\begin{bmatrix}
\psi(t) \\
\dot{\psi}(t) \\
\alpha(t)
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
1
\end{bmatrix}
\begin{bmatrix}
u(t) + d(\alpha, t)
\end{bmatrix}
\end{aligned}
$$

(1)

where $K_E$ is the NLG stiffness, $C_D$ is its damping constant, $J$ is the moment of inertia, $F_z$ is the weight force that acts on the NLG and $V$ is the travelling speed. Moreover, $e$ is the caster length, $a$ is the tire half-contact length with the ground, $\kappa$ is thread width tyre moment while $C_M$ and $C_F$ are tire-ground interaction cornering coefficients, and $\sigma$ is the relaxation length. In equation (1) $u(t)$ is the control torque applied on the NLG leg by the actuator while $d(\alpha, t)$ is representative of the tire-road nonlinear interaction. For the definition of the nonlinear term and for more detail about the shimmy governing equations the interested reader is referred to literature [11].

2.2 MSAC with Anti Windup

The define the control system, the nonlinear term $d$ in the problem governing equation is treated as a disturbance, thus the plant can be represented by a linear transfer function $G$. To safely apply the MSAC scheme, the system should meet the Kalman–Yakubovich–Popov condition [13]. A SISO system satisfies such condition when the transfer function is Almost Strict Positive Real, this implies that all zeros of $G$ are negatives, the numerator leading coefficient is positive the transfer function relative degree is 1. In the present case, only the relative degree condition is not met and, for this reason, a Feedforward Compensator PFC is added in parallel to let the augment system meets the requested condition. The transfer of the PFC is $G_{pfc}(s) = 0.00625(10s + 1)^{-1}$; for the tuning procedure of the PFC the interested reader is referred to literature [11]. Once the augmented system is obtained, the output feedback MSAC scheme can be introduced as

$$
u(t) = \Gamma_p e^3(t) + K_j(t)e(t)
$$

(2)

being $\Gamma_p$ an invariant parameter while $K_j(t)$ is an adaptive gain that varies as

...
\[ \dot{K}_i(t) + \eta K_i(t) = \Gamma_i(t)e^2(t) \]  \hspace{1cm} (3)

where \( \Gamma_i \) is another invariant parameter while \( \eta \) is called forgetting factor and acts reducing the KI value when the error \( e(t) = y_m(t) - y(t) \) between the system and the model reference output becomes zero. For more detail about the formulation see [11, 10]. Figure 1 shows the architecture of the controlled system putting in evidence the presence of the actuator saturation and the back-calculation anti-windup scheme characterized by the constant \( T_{\text{wup}} \).

**Figure 1.** MSAC applied to the augmented system with anti-windup scheme

### 3. Simulation Results

The NLG model parameters used for the simulations are: Inertia \( J = 1 \) kg m\(^2\); stiffness \( K_i = 100 \) kN m/rad; damping constant \( C_d = 20 \) Ns/m rad; caster length \( e = 30 \) cm; half contact length \( a = 10 \) cm; constant of thread width tyre moment \( \kappa = 270 \) Nm/rad\(^2\); self-aligning stiffness \( c_{y} = 20 \) rad\(^{-1}\); limiting angles \( \delta_f = 5 \) deg and \( \delta_m = 10 \) deg. The NLG undergoes an initial rotation angle \( \psi_0 = 5.73 \) deg. The maximum control torque that can be applied by the controlling actuator is \( M_{C,\text{sat}} = 2 \) kNm [1]. Two different values of the taxiing speed are considered, namely \( V = 75 \) m/s and \( V = 100 \) m/s whilst three different weight configurations are studied by multiplying the force \( F_z = 9 \) kN by the weight factor \( w_f = \{0.7, 1.0, 1.3\} \). On the other hand, the adaptive control system parameter are set as: \( \Gamma_p = 10^6 \) Nm/deg\(^2\); \( \Gamma_c = 10^6 \) Nm/deg\(^2\) s\(^{-1}\); \( \eta = 10^{-3} \) s\(^{-1}\). For more details about the MSAC design the interested reader is referred to [11]. Last, the back calculation anti-windup constant is set to \( T_{\text{wup}} = 0.318 \) s.

Figures 2 gives simulation results in terms of shimmy angle and controlling torque time histories. In particular, figure 2 presents results obtained for three distinct values of the weight factor \( w_f \), and, when \( w_f = 1 \), it shows a comparison between literature results and the shimmy response obtained by the proposed controlling technique, see figure 2 (a) and (b). The literature results are taken from [15] where a controller based on parallel-distributed compensation (PDC) is proposed to have an asymptotically stable closed loop system; however the modelling approach proposed in [15] does not account for actuator saturation. This implies that the response of the system in term of shimmy rotation is good as the shimmy oscillation is damped in about 0.04 seconds but the torque requested to control the shimmy vibration reaches a value that is about three times greater than the actuator limiting torque \( M_{C,\text{sat}} \) [1]. By using the MSAC approach taking into account the actuator saturation it is obtained that the control system isn’t capable of damping the shimmy phenomenon. Looking at figure 2 (a) and (b) it can be noted in fact that the shimmy angle response tends to diverge in the analysed time window and the actuator torque response continues to oscillate between the maximum and minimum saturation limits. On the other hand, when the AW-MSAC scheme is used the system kinematic response becomes alike the PDC one [15] and the shimmy vibration is damped in about \( T_{\text{settling}} = 0.027 \) s while the control torque time history reaches saturation limits only during such short time interval, after \( T_{\text{setting}} \) the \( M_c \) response no longer oscillates and tends to zero.
Looking now at Figure 2 from (c) to (f) it can be appreciated the effect of weight on the system response and the anti-windup scheme is still useful. An increase of 30% weight slightly extends the settling time while a reduction of 30% weight slightly reduces the duration of the shimmy oscillation. In particular when $w_f=1.3$ the settling time percentage difference with respect to the reference case, i.e. $w_f=1$, is about 3.7% which corresponds to one thousandth of a second; on the other hand, it reduces to 0.025 s when $w_f=0.75$. The effect of weight on the system response can thus be considered negligible in the present initial disturbance study case.

Another different disturbing condition is now considered with the aim of numerically investigating the robustness to weight variation of the simple adaptive shimmy suppression system. The study case goes under the name of tire damage; an external moment of 1 kNm is applied to the tire for 0.2 s with $V=100$ m/s and the system response in terms of the fork-wheel rotation angle and control moment requested by the anti-windup MSAC scheme is computed for the three distinct weight factors aforementioned. Figure 3 gives a close-up view during the disturbing event. It can be appreciated that the settling time is almost unchanged despite of the weight variation while the amplitude of the fork-wheel assembly rotation angle is only slightly influenced and its value varies between 0.3 deg and 0.38 deg which are far below the maximum acceptable rotation angle [8].
4. Conclusions
A numerical study has been presented in this work to investigate the response of an adaptive shimmy suppression system. The active shimmy damping system is obtained by implementing a Modified Simple Adaptive Controller with a Parallel Feedforward Compensator to meet the Kalman–Yakubovich–Popov condition. Moreover, a back-calculation anti-windup scheme has been also implemented in order to avoid negative effects caused by the actuator torque limitation. The numerical investigation on the weight effects has shown that the dynamic response of the proposed adaptive MSAC based shimmy suppression system is soundness despite of weight variation and can manage the NLG behaviour even in presence of possible aircraft overweight conditions.

5. References

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