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Modeling and Simulation of Shimmy Behavior in an Aircraft Steering System Using Bondgraph-based Software

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Abstract. Most aircraft steering architectures do not actuate the system during landing, allowing the aircraft to align itself to the runway track. This lack of control results in a condition where the wheels may experience high-amplitude and high-frequency oscillations, known as the shimmy effect. One of the methods for preventing this phenomenon from happening is to connect the piston chambers to anti-shimmy valves, acting as a damper for the steering oscillation. In this paper we present the modeling and simulation of shimmy in an aircraft steering wheel using a bondgraph-based software. The paper presents a simplified model of a rack-pinion steering wheel system under landing conditions. Later, anti-shimmy valves are included and their effect in the model dynamics is evaluated. Tire-pavement interactions are modeled through the Pacejka Formula, informally known as the ”Magic Formula”, which was adapted for the aeronautical context. Simulations are made using Simcenter Amesim 15.2, where the model is implemented using components found on the Student Version library. The model fully captures the shimmy behavior and allows one to visualize the importance of the anti-shimmy valve diameter on steering dynamics.

Keywords: AMESIM, Aircraft Steering System, Shimmy

1 Introduction

The steering system is part of the aircraft nose landing gear system. Its function is to provide maneuverability to the aircraft during taxi, take-off and landing. A good steering system will reduce turn-around-time and extend the brake system lifespan.

Most hydraulic steering architectures do not actuate the steering system during landing. This leaves the nose landing gear uncontrolled, but allows the aircraft to self align to the runway track, taking advantage of the aircraft velocity vector to increase stability and preserve the landing gear components. However, a problem arises from this lack of control. The nose landing gear may start to oscillate, originating a phenomenon know as shimmy.

Shimmy is a high-frequency, high-amplitude oscillating movement of the wheel that may occur at high speeds on cars, motorcycles and also on aircraft. It may cause the aircraft to lose control, compromising the safety of take-off and landing operations, besides wearing off hydraulic and mechanical components. One of the methods for preventing this phenomenon is to connect the chambers of the hydraulic system to anti-shimmy valves, which act as a damper for the steering oscillation.

Complex models have been utilised to represent the shimmy dynamics [1] and its interaction with the hydraulic system [2]. It is also usual to have complex representations of the hydraulic components of the aircraft such as the electro-hydraulic servo valves (EHSV) [3]. This work aims at the opposite direction: to model the shimmy behaviour with a simple representation of the hydraulic system and of the steering system.

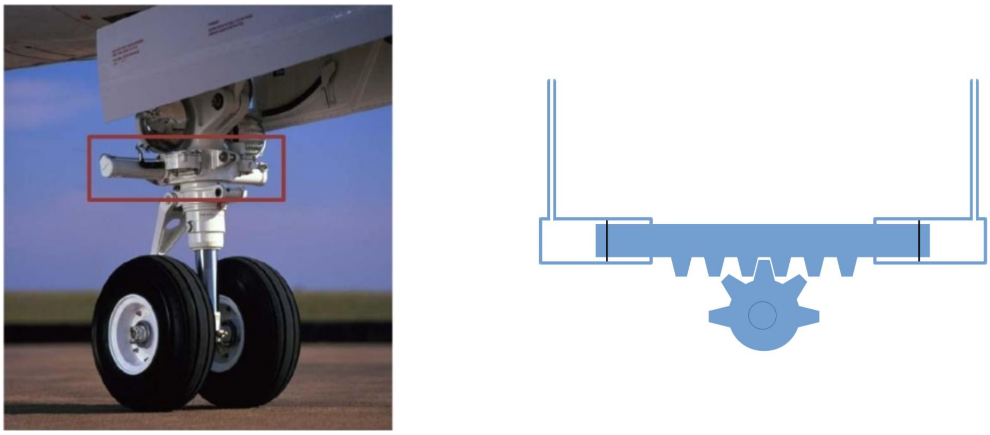
This paper presents a simplified model of a rack-pinion steering system under landing conditions that may be used for teaching and academic purposes, preliminary design of steering systems and for better understanding of shimmy dynamics. The proposed model can be completely implemented utilizing the student version of the software Simcenter Amesim, a popular simulation platform developed by Siemens, in its version 15.2.

The paper is organized as follows: section 2 expands on the architecture of a rack-pinion steering system. Section 3 explains how the shimmy behaviour is generated, while section 4 presents the simplified steering system model implementation. Section 5 presents the behaviour captured by the model, and in section 6 the final remarks are done.

2 Rack-Pinion

There are several steering architectures available to aircraft landing gear, such as the banana lever, the twin actuator, the travelling cylinder and the oscillating cylinder. One of such options is the rack-pinion system.

The rack-pinion system was popularized on the decade of 1960, and since then has been a frequent choice, specially on smaller aircraft. In this architecture there are two hydraulic cylinders at the extremities of the rack, while the pinion is connected to the landing gear cylinder, which drives the wheel direction. It has the advantages of lower hydraulic volume requirements, constant steering torque and the possibility of effective steering at greater steering angles [4]. Figure 1a shows an example of rack-pinion system highlighted on an ERJ145 aircraft, while 1b shows a simplified drawing of an aircraft rack-pinion hydraulic system. Figure 2 shows a simplified lateral view of the nose landing gear.



(a) (b)

Figure 1. (a) ERJ145 nose gear fig. (taken from [5]), and (b) Rack-pinion simplified diagram.

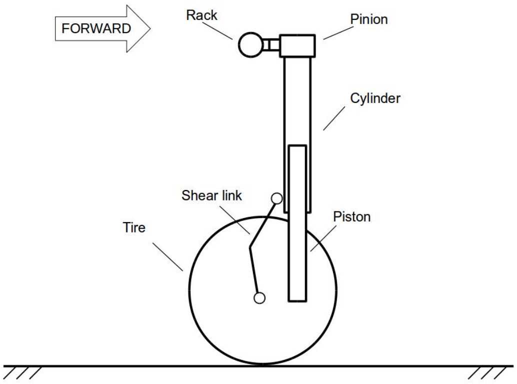


Figure 2. Schematics of nose gear lateral view.

The rack-pinion system has two main modes of operation: engaged and free caster. On engaged mode, the steering system is active and hydraulic power is available to actuate the nose wheel according to pilot's commands, while on free caster, actuator chambers are connected to each other, disengaging the hydraulic power. The free caster mode is utilized on late take-off, early landing and also on towing operations, while the engaged mode is utilized during low speed motion on ground (early take-off, late landing and taxi operations) [5].

It is important to note that, as our concern is immediately after nose wheel touchdown until a few seconds later, free caster is on, which means there is no hydraulic power transmitted to the chambers. As mentioned in the introduction, there are a number of reasons for that:

- To allow the wheel to naturally align to the direction of movement, helping the aircraft to stabilize itself at the early stages of landing;
- To protect mechanical and hydraulic components;
- To neglect wheel authority, since at wind speeds above certain level, the rudder is the primary source of on-ground directional control;

3 Shimmy Effect

Shimmy is a phenomenon where the wheels oscillate in a high-frequency and high-amplitude movement, usually without any means of active control. This effect occurs as a dynamic response of the system, where a steer perturbation generates restoring forces capable of sustaining the oscillatory movement. Shimmy can lead to on-ground maneuverability loss, tire burst, premature wear of components or even sudden mechanical failures, conditions that highly endanger the operation. Thus, the system must be demonstrated shimmy-proof for an aircraft to be certified.

Shimmy can occur on both types of landing gears, but it is more likely to happen on nose gears. Firstly because the main landing gears have a high torsional stiffness, thus not allowing high rotation amplitudes. On the other hand, nose landing gears are usually installed with a steering system, whose main function is to enable rotation around its vertical axis. Besides, the fact that the steering system is not active during landing implies additional means to prevent wheels from developing unstable oscillations.

The usual solution for the shimmy problem is to adopt passive dampers, capable of dissipating the steering system's rotational energy, decreasing the movement amplitude. The idea is to properly dimension the dampers so that system behaves closely to a critically damped system. These dampers may be of different kinds. For example, on mechanically actuated steering systems, it is often used external axial dampers, mounted with a lever arm relative to the steering axis, thus producing a damping torque. Hydraulic actuated steering systems usually take advantage of their own fluid lines, using orifice valves to provide the required damping.

4 Steering System Model and Simulation

The steering system model can be divided into two main parts: the rack-pinion model (comprising the hydraulic system and the mechanical and structural components of the steering wheel) and the tire-pavement model, which represents the dynamics that emerges between tire and pavement. The full model is presented on Fig. 3, and each subsystem is detailed in the next subsections. The model was implemented using only the components library available on student version 15.2 of the software AMESIM.

The system was modelled after the characteristics of the ERJ145 steering wheel system, which is not presented in this work. On the other hand, the model parameters can be easily adapted to any aircraft. Whenever assumptions of ideal behaviour were made, these are stated.

4.1 Mechanical-Hydraulic Model

On the usual architecture employed in real aircraft, a bypass system is used to activate free caster or engage the hydraulic actuators, as can be seen in [2]. Figure 3 shows the simplified steering system model. As was introduced earlier, the scenario of interest is the landing condition, implying steering actuation disengaged, i.e., free caster mode on.

In the absence of a two-ended rack-pinion system on AMESIM student version, the two symmetric hydraulic actuators were substituted by a single actuator with double hydraulic chamber and rods on both sides of the piston. The rack, which would go in between the two actuators in the real system, was placed at the tip of one of the rods. This decision follows from the assumption that the rack is a rigid body. Finally, given the considered time frame, it was hypothesized that the internal and external leakages could be disregarded.

The hydraulic model is also composed of two relief check valves, two anti-cavitation valves and an EHSV, that remains on neutral position through the entire simulation. The anti-shimmy valves are the components inside the orange rectangle, and are removed from the model to simulate the undamped system.

On Fig. 3, the green subsystem represents the mechanical components of the nose landing gear. The rack-pinion and cylinder inertia were concentrated on J1, while the wheel and tire inertia were condensed on J2 (rigid coupling assumption). The coil embodies torque links finite stiffness, that transfer the torque from pinion axle to wheel.

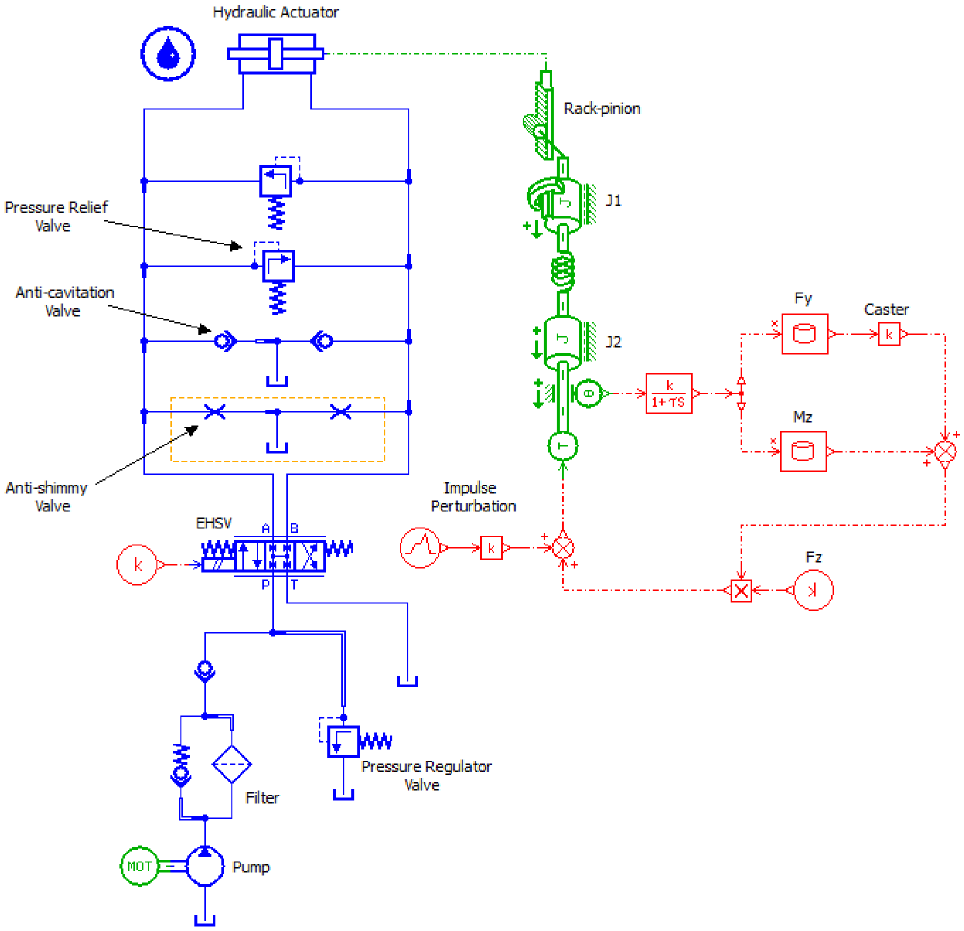


Figure 3. AMESIM model.

4.2 Tire-Pavement Modeling

The function of the steering system is to generate the external forces responsible for allowing the aircraft to perform yawing maneuvers while on ground. These lateral forces are a response of the tire-pavement interface when subjected to slip, commonly known as the tire slip angle. Thus, in order to accurately assess the steering system behavior, a means to calculate these forces must be provided.

The herein used formulation is called "*Magic Formula*", developed by Pacejka [6], being a consolidated mathematical model that characterizes the tire-pavement interaction. This formulation relies on empirical data to which the model must fit. Nevertheless, for the scope of this work, the curve fitting was estimated due to the lack of available data.

The formulation for both lateral force and self aligning torques are the same, in which only the coefficients (B_α, C_α, D_y and E_α) differ from each other. The "*Magic Formula*" is depicted on the following equation, in a simplified manner, disregarding tire pressure and camber effects. Although the tire-pavement model has explicit formulae for the forces, its was applied on the simulation environment via lookup tables, with no loss of accuracy.

$$X = D_y(C_\alpha \arctan((1 - E_\alpha)B_\alpha\alpha + E_\alpha \arctan(B_\alpha\alpha)) \tag{1}$$

Generally, nose wheels adopt an offset distance (caster arm) from the steering axis. This condition is depicted on Figure 4. This configuration leads the lateral force to generate a counter-acting torque around the steering axis, acting to decrease the slip angle (α), comprising a stabilizing force. On the other hand, the self aligning torque may act on both directions, depending on the coefficients and on the slip angle magnitude.

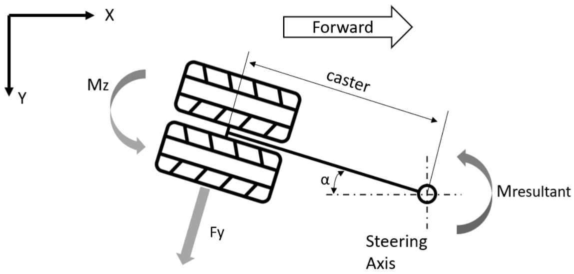


Figure 4. Steering system configuration.

The total torque acting around the steering axis is then given by the following equation:

$$M_{resultant} = F_y.caster + M_z \tag{2}$$

At last, a transient behavior was introduced on the tire-pavement generation of forces, aiming to increase accuracy. A first order linear dynamics, found on [6], is applied to the calculation of instantaneous tire slip angle, which then feeds the equation 1. Equation 3 presents the formulation, where V_x is the longitudinal velocity, V_y is the lateral velocity, and σ_y is the lateral relaxation length.

$$\sigma_y.\dot{\alpha} = -V_x.\alpha + V_y \tag{3}$$

4.3 Simulation

Equation 2 was translated into a pair of lookup tables and included in the model according to the schematic in red on Fig. 3. The total torque is corrected by a value proportional to the aircraft weight (through the parameter F_z) before being applied to the model.

The simulation time was established as 3 seconds after determining that this length of time was large enough both to observe the emerging shimmy behaviour and the shimmy attenuation when using the shimmy dampers. The moment the nose wheel touches the runway pavement was simulated through an impulsive signal at the instant 0.3 seconds, proportional to the aircraft weight.

5 Results

5.1 Without shimmy valve

The model was initially built and simulated for with the hydraulic system without shimmy valves. Figure 5 exhibits the nose gear wheel angle when there are no anti-shimmy valves. It can be seen that, after the initial perturbation, the system achieves a high-amplitude oscillation with frequency of approximately 5 Hz and amplitude of about 11 degrees. Forces and moments on the system components and pressure on all components of the hydraulic line were analyzed to ensure that the operating conditions were within system limitations (for example, to ensure that there was no overpressure on the hydraulic line). All observed values were compatible with the ERJ145 landing gear operation.

From the obtained results, it is possible to say that the effect of shimmy was correctly captured.

5.2 With shimmy valve

The anti-shimmy valves where included in the model according to Fig. 3 and the same initial conditions where applied. It was possible to observe that the wheel oscillations were greatly attenuated, and as expected, shimmy did not occur. This result is presented on Fig. 6. Once more, all the observed forces, moments and pressures on the system were compatible with the operating conditions.

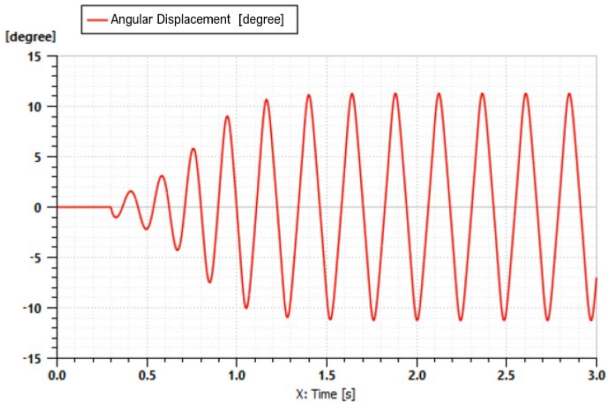


Figure 5. Nose gear angle [degrees] w/o shimmy valve.

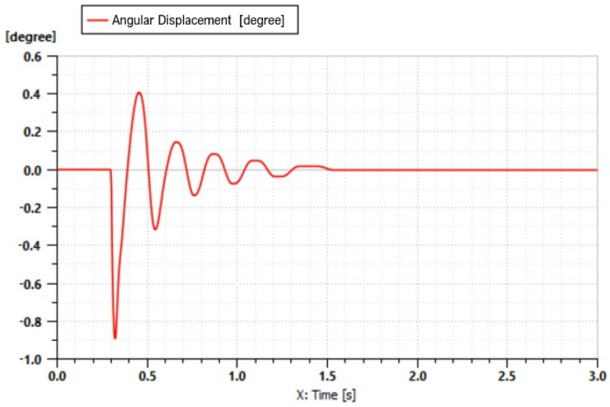


Figure 6. Nose gear angle [degrees] without shimmy valve.

5.3 Model limitations

The model captures the shimmy behaviour for the system, and is adequate to preliminary studies and academic purposes. Still, a few points are worth mentioning:

1. The mechanical model of the landing gear was greatly simplified, and several components of the steering system were overlooked for simplicity sake. Of particular note, the landing gear suspension was also disregarded. The aircraft landing gear is a complex system, were each component has multiple functions on a variety of systems, and it is not really possible to decouple one of its functions from another.
2. The hydraulic model has the assumption of no fluid heating, what might impact the shimmy behaviour by changing the characteristics of the fluid.
3. The tire-pavement interaction is simplified, with assumptions that the tire will not deform or heat during the landing of the aircraft.
4. At last, the deceleration of the aircraft throughout the landing phase was not included on the developed model. It impacts tire-pavement dynamics, the normal forces on the landing gear and aircraft control.

6 Conclusion

This paper presents a simplified aircraft steering system model with rack-pinion architecture that captures the shimmy dynamics during landing operation. While there are some points to be noted for a more comprehensive representation of landing gear system, steering system and shimmy effect, the model is adequate for an initial approach to the problem, and can be used for academic and teaching purposes, for better understanding of the phenomenon and for preliminary designs and evaluations. The model was implemented on AMESIM with components available on the student version of the software, which further distinguishes its value for academic usage.

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