STUDY OF SHIMMY IN INDUSTRIAL CONTEXT

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Abstract: An aircraft landing gear may experiment self-sustained oscillations (termed shimmy) due to a transfer of energy between the modes of the system, via the interaction between tires and ground. This oscillatory phenomenon should be studied because it may lead to structural damages, up to the rupture of landing gear. After the presentation of mathematical formulation and of model calibration used to simulate the shimmy phenomenon, industrial context of shimmy analysis is illustrated with a generic application. Based on this experience, some ways of improvement are formulated in order to make the shimmy analysis more predictive.

1 INTRODUCTION

Vibrations resulting from elastic behavior and from dynamic loads may cause structural damages. A significant example concerns the spectacular collapse of Tacoma Narrows Bridge in Washington State in 1940, only four months after its completion (figure 1). Due to a lack in conception, some natural frequencies of the structure (excited by wind) were self-sustained due to a coupling phenomenon, causing a steady increase in amplitude until the bridge was destroyed. Another structural excitation by aerodynamic coupling is given by flutter phenomenon for an aircraft, what may cause a structural rupture.

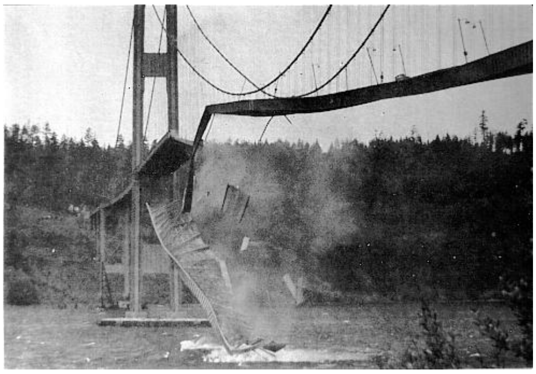

Figure 1: Tacoma Narrows Bride destruction due to modal excitation by wind

Shimmy [1] is a self-excited oscillation of an aircraft landing gear that may occur both on taxiing, landing or take-off operations. These oscillations are driven by the interaction between tire and ground, coupling natural modes of landing gear structure.

Modal coupling gives birth to a transfer of energy from one mode to another mode (typically from lateral mode to torsion mode). Self-sustained oscillations are problematic if the damping level associated to one mode (typically the torsion mode) becomes negative. In that case, shimmy oscillations are divergent and may cause the failure of landing gear.

In industrial context, prediction of shimmy oscillations is essential for many reasons (passenger comfort, security requirements etc). Risks of shimmy oscillations should be minimized before any flight operation, supported by specific documents for justification. Mitigation of shimmy risks may drive the elaboration of specific sub-elements or landing gear modification, from structural modification (change in mass or stiffness repartition) up to architectural modification (add-on of anti-shimmy system).

Dassault Aviation mathematical approach to model shimmy is based on previous studies ([5], [6], [8] and [9]). The resulting linearised modal stability analysis is described in details in the first section of this article and a short comparison with another approach (based on a time domain solver) is proposed in the second section. Generic application of shimmy analysis in an industrial context is presented in the third section. Based on Dassault Aviation experience, ways of improvement are formulated in the fourth section.

2 MATHEMATICAL FORMULATION FOR SHIMMY

2.1 Dassault Aviation methodology

Specificity of Dassault Aviation shimmy approach is performing a linearised modal stability analysis (denoted as modal analysis in this article) rather than a full non-linear time domain analysis of landing gear behavior.

This modal analysis is divided into several steps.

- First step is devoted to the creation of a finite element model of landing gear. This model should be calibrated (in terms of stiffness or mass repartition), based on experimental data (cf sub-section 3.1 of this article).
- Second step consists in defining configurations for which shimmy analysis is performed. For Dassault Aviation shimmy analysis, the main configuration parameter is the stroke value when landing gear is in contact with ground.
- Third step concerns the evaluation of mass, damping and stiffness matrices (respectively designed M, B and K) of landing gear structure for each configuration. Dimension of the three matrices M, B and K corresponds to the total number of landing gear degrees of freedom (DoFs) for the finite element model. These matrices are representative of physical characteristics of landing gear (such as its stiffness or mass repartition) but also of a given configuration.
- Fourth step is devoted to modal analysis. Given a landing gear configuration, modal analysis consists in performing an eigenvalue resolution to evaluate frequencies, damping levels and shapes (ie eigenvectors) of modes at a given aircraft velocity (imposing a rotative velocity for the wheel under no slip hypothesis). The principle of shimmy analysis is to evaluate the influence of aircraft velocity on landing gear modal stability. Consequently, output data are not scalar values of landing gear response but curves versus velocity aircraft for frequency and damping levels associated with landing gear modes.

The main principle of Dassault Aviation approach is to get free from all sources of non-linearity (like free-play or friction) appearing at low amplitude of excitation. A linearised model is then used to perform modal analysis. During calibration of landing gear model (detailed in sub-section 2.5.1), asymptotic linear behavior of landing gear is searched, far from any possible non-linearity. Limit cycle oscillations are not evaluated with such a linear model. However, limit cycle oscillations are less problematic than divergent oscillations and are often reduced by playing with non-linearity sources (like the gap between torque links). However, a complementary analysis (focused on the non-linear behavior of landing gear) is a possible way of improvement for Dassault Aviation methodology.

Damping level may arise from two origins: the landing gear structure itself (structural damping) and the modes coupling associated with the rolling system (shimmy damping). Contrary to shimmy damping, structural damping (which is always positive) is taken into account in modal analysis as a conservative estimation due to a lack of knowledge.

The influence of the aircraft flexibility on the landing gear modes may be evaluated with the finite element model. However, this influence is negligible on Dassault Aviation aircrafts.

2.2 No ground/tire contact

Landing gear DoFs include the six DoFs of the center of wheel, denoted by $(T_x, T_y, T_z, R_x, R_y, R_z)$ in ground axis. The three main modes of the landing gear are longitudinal, lateral and torsion modes (figure 2), respectively associated with T_x, T_y and R_z motions of wheel center[1].

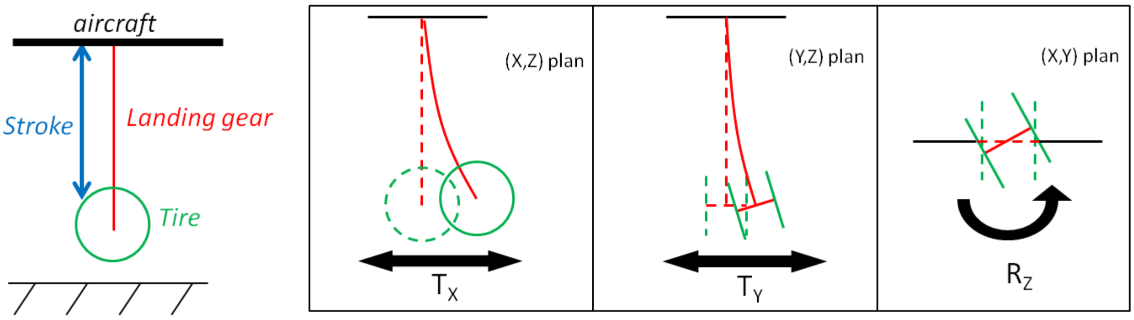

Figure 2: Longitudinal, lateral and torsion modes (no tire/ground contact)

When tire is not rolling on ground, landing gear modes (also called natural modes) are orthogonal and so totally uncoupled.

The modal analysis is based on the following fundamental equation of dynamics.

$$M_0 \ddot{X}_0 + B_0 \dot{X}_0 + K_0 X_0 = 0 \tag{1}$$

Where M_0, B_0 and K_0 design mass, damping and stiffness matrices when landing gear is not rolling on ground. Variable X_0 corresponds to vector of landing gear DoFs ($\dot{X}_0$ and

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[1] Realistic case is a little more complex because modes are rarely associated with only one motion. However, a longitudinal, a lateral or a torsion mode are generally detected, corresponding to modes for which the T_x, T_y or R_z motion of the wheel center is predominant respectively.

$\ddot{X}_0$ denoting the first order and the second order time derivatives of X_0), including the six wheel DoFs.

Determination of natural modes of landing gear constitutes important pieces of information for shimmy analysis for two main reasons.

- Natural modes represent useful data to calibrate landing gear model (see sub-section 2.5.1).
- Natural modes (associated with a motionless landing gear) are starting points of shimmy analysis, for which aircraft velocity is the varying parameter.

2.3 Ground/tire contact (modal shimmy analysis)

Tire/ground contact combined with a non-zero aircraft velocity produces couplings among the six DoFs $(T_x, T_y, T_z, R_x, R_y, R_z)$ of landing gear. In a first approximation [7], these coupling effects are reduced to four effects (figure 3), namely gyroscopic effect, adhesion effect, cornering effect and yawing effect.

Without considering the last two effects which modify dimension of matrices (as explained below), coupling effects consist in additional terms for equation (1).

$$M_0\ddot{X}_0 + B_0\dot{X}_0 + K_0X_0 + T_{gy}(V,\dot{X}_0) + T_{ad}(\ddot{X}_0) = 0 \tag{2}$$

Where $T_{gy}(V,\dot{X}_0)$ and $T_{ad}(\ddot{X}_0)$ are additional terms corresponding to gyroscopic effect and adhesion effect respectively. Gyroscopic term depends on velocity V of the aircraft, considered as a constant variable during modal resolution. The four coupling effects are expressed in the six wheel DoFs basis, before their projection into the landing gear DoFs basis.

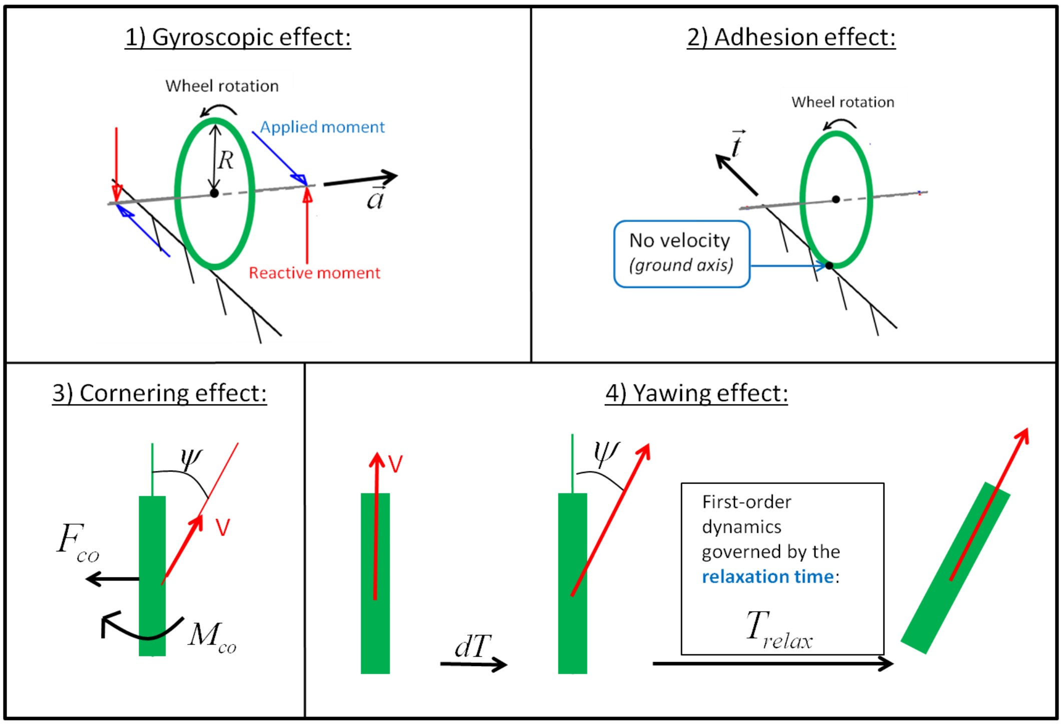

Figure 3: Illustration of the coupling effects (inferior schemes are top views)

These coupling effects (illustrated in figure 3) are detailed below.

- Gyroscopic effect. This effect comes from dynamics of a rotative system. The mathematical formulation is given by:

  $$T_{gy}(V,\dot{X}_0)=\frac{JV}{R}\begin{pmatrix} 0 & -a_x & a_y \\ a_x & 0 & -a_z \\ -a_y & a_z & 0 \end{pmatrix}\begin{pmatrix} \dot{R}_x \\ \dot{R}_y \\ \dot{R}_z \end{pmatrix} \tag{3}$$

  Where R and J denote radius and rotation inertia of wheel, tire and eventually brakes assembly around wheel axis $\vec{a}$ respectively. Gyroscopic effect produces an anti-symmetric coupling among rotational velocities of landing gear.

- Adhesion effect. Based on the hypothesis that wheel is rolling on ground under no slip condition, an additional inertia term for translation movement along the wheel orientation axis (in the ground plan) is added to the mass value. The mathematical formulation is given by:

  $$T_{ad}(\ddot{X}_0)=\frac{J}{R^2}\begin{pmatrix} t_x t_x & t_x t_y & t_x t_z \\ t_y t_x & t_y t_y & t_y t_z \\ t_z t_x & t_z t_y & t_z t_z \end{pmatrix}\begin{pmatrix} \ddot{T}_x \\ \ddot{T}_y \\ \ddot{T}_z \end{pmatrix} \tag{4}$$

  Where $\vec{t}$ is the wheel orientation projected on ground. Adhesion effect produces an additive symmetric mass matrix to the natural landing gear matrix M_0.

- Cornering effect. When velocity direction is different from wheel orientation, creating a non-zero yaw angle $\psi(V)$, cornering loads are applied to wheel through a lateral force F_{co} (also called cornering force) and a torsion moment M_{co} (also called self-alignment torque). These cornering loads are directly proportional to the yaw angle and are written as following:

  $$\begin{cases} F_{co} & = & \alpha_{co}\psi(V) \\ M_{co} & = & \gamma_{co}\psi(V) \end{cases} \tag{5}$$

  Where α_{co} and γ_{co} are cornering coefficients directly linked to physical characteristics of tire.

- Yawing effect. Time evolution of cornering loads is controlled by the yaw angle, which evolutes accordingly to the following first-order equation:

  $$\psi(V)+T_{re}\dot{\psi}(V)=R_z+k(V)\dot{T}_y \tag{6}$$

  Where $k(V)$ is a term depending on aircraft velocity. Relaxation time T_{re} is directly linked to physical characteristics of tire.

The last two effects introduce a new DoF for landing gear structure via the yaw angle. This new variable is linked to the other DoFs via the first-order equation of yawing effect on the one hand and via cornering loads on the other hand.

When wheel is rolling on ground, the fundamental equation of dynamics becomes:

$$M\ddot{X} + B\dot{X} + KX = 0 \tag{7}$$

Where X is equal to $\begin{bmatrix} X_0 \\ \psi(V) \end{bmatrix}$.

Influence of coupling effects on the 3 matrices M, B and K is highlighted by figure 4.

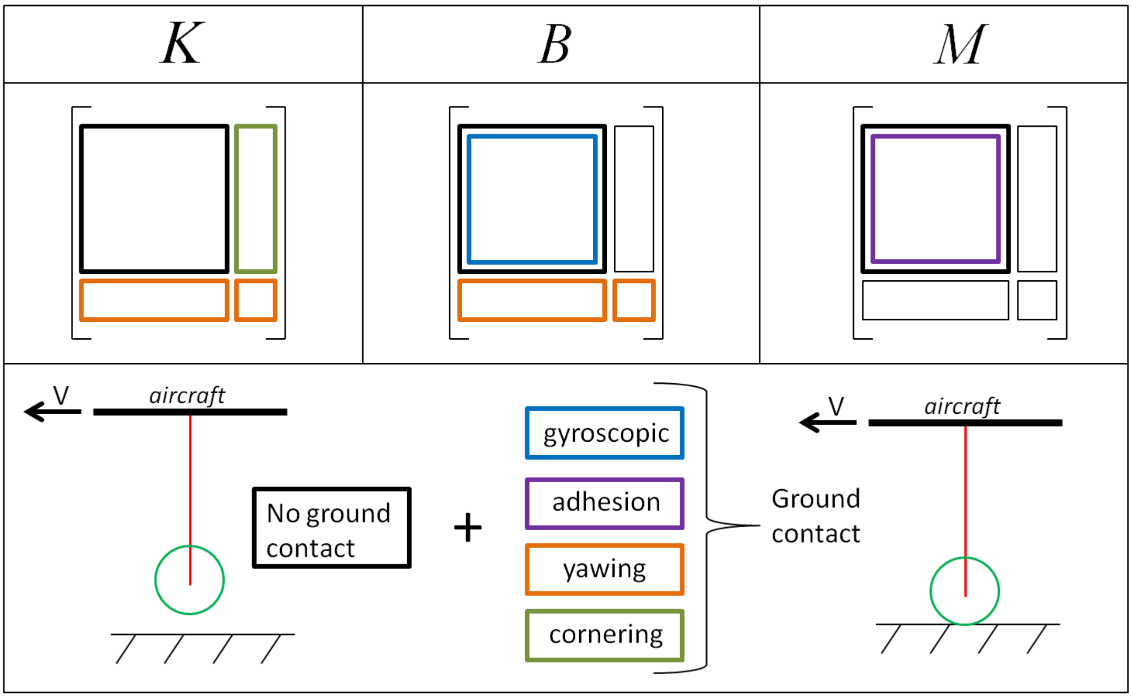

Figure 4: Modification of landing gear matrices when wheel is rolling on ground

So, all these effects directly influence the modal analysis of landing gear, making the shimmy oscillations possible. In particular, positivity of damping levels is no longer guaranteed.

2.4 Time shimmy analysis

Time shimmy analysis consists in solving iteratively the time version of equation (7), corresponding to the following equation.

$$M(X(t))\ddot{X}(t) + B(X(t))\dot{X}(t) + K(X(t))X(t) = F(t) \tag{8}$$

Where t and $F(t)$ design time variable and vector of load respectively. Mass, damping and stiffness matrices depend on the landing gear configuration. At each time iteration step, landing gear matrices are updated, what makes it possible to take into account non-linearity.

Output data of time shimmy analysis are no longer frequencies and damping levels (modal shimmy analysis) but time evolutions of landing gear DoFs $X(t)$ in response to $F(t)$.

A shimmy phenomenon is identified when at least one landing gear motion presents limit cycle or unstable divergent oscillations.

2.5 About non-linearity of landing gear

In Dassault Aviation strategy, implemented model is representative of the asymptotic behavior of landing gear, free from non-linearities of behavior appearing at low amplitude of motion. A linearization operation is included for both calibration of landing gear structure and determination of tire parameters.

2.5.1 Landing gear structure

When landing gear structure is experimented for model calibration, some non-linearities are detected like friction or free-play. Linearization of landing gear behavior is an essential step of Dassault Aviation landing gear calibration.

Two test campaigns are sufficient to perform landing gear calibration.

- Static tests, devoted to stiffness repartition
- Dynamic tests, devoted to mass repartition.

During static tests, landing gear (mounted on a rigid rig or directly on the aircraft) is loaded by jacks at the wheel center point (figure 5). Typical instrumentation consists in almost 20 potentiometers (or laser tracking systems) dispatched on the landing gear to measure local displacements. Several configurations are tested, knowing that a configuration is defined by the stroke and the orientation of imposed loads (mainly longitudinal, lateral and torsion loads are considered). It represents at least 9 configurations (a minimum of 3 stroke values are typically considered). For a given configuration, displacements are stored for several load intensities

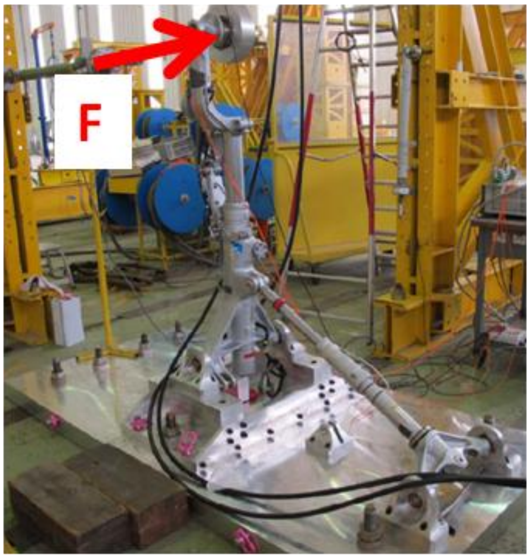

Figure 5: Picture of static test facility (imposed load F)

As the asymptotic behavior is searched, the first step of post-processing of experimental data is to ensure that employed loads are sufficiently high to get free from non-linearities associated with “small” deformation. Such verification is performed by plotting the displacement linked to a specific potentiometer versus the intensity of imposed load for a given configuration (figure 6). When linear asymptotic behavior is detected, landing gear stiffness is deduced from the slope of linear comportment.

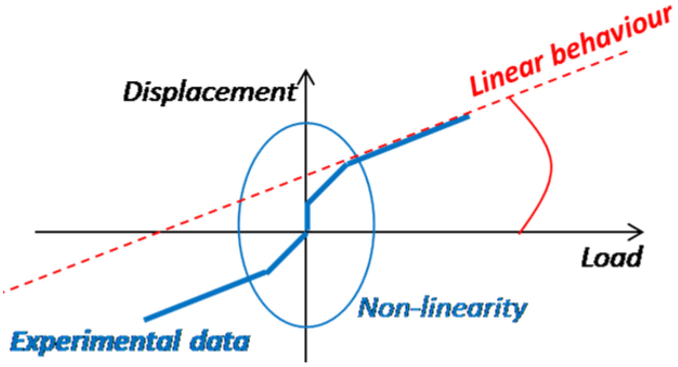

Figure 6: Post-processing of experimental data from static tests

Once stiffness repartition is calibrated by static tests, dynamic tests are used to calibrate mass repartition.

Compared to static test conditions, jacks are replaced by dynamic shakers and potentiometers are replaced by accelerometers for dynamic tests (figure 7). For a given configuration (defined by stroke value and orientation of imposed vibrations), natural frequencies of the landing gear are determined, using specific techniques like Phase Resonance Method or Phase Separation Method [3]. As asymptotic behavior is searched, this operation is made for several amplitudes of excitation because of non-linearities associated with “small” vibration levels.

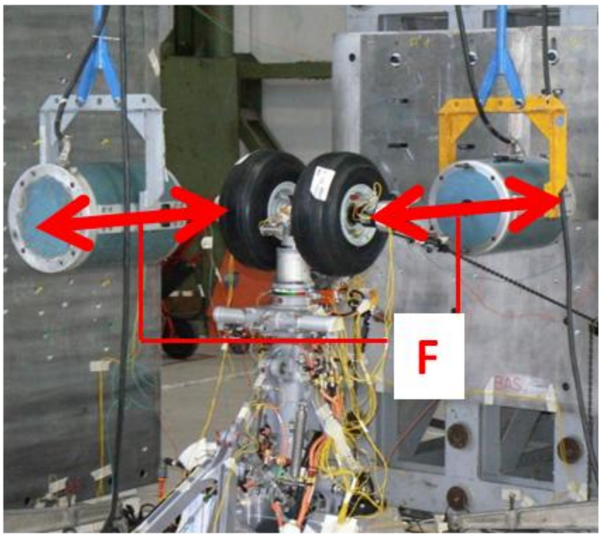

Figure 7: Picture of dynamic test facility (imposed load F)

Post-processing of experimental data consists in plotting the amplitude of displacement multiplied by the natural frequency of landing gear versus the amplitude of displacement for a given configuration (figure 8). The reason why vertical axis is the amplitude of displacement multiplied by the natural frequency rather than the natural frequency is that evaluation of asymptotic linear behavior is easier on a non-zero slope line. For sufficiently strong amplitudes, the structure has a linear behavior. Natural frequency (free from non-linearities) is deduced from the slope of linear comportment.

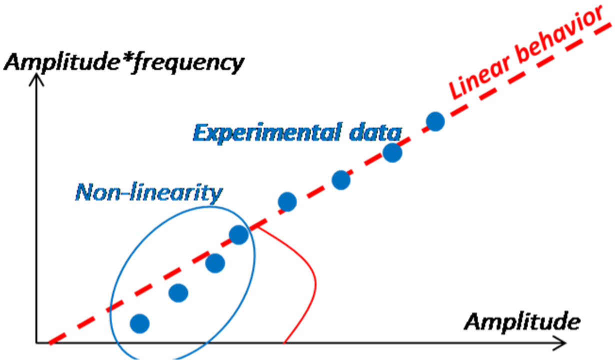

Figure 8: Post-processing of experimental data from dynamic tests

2.5.2 Tire

In Dassault Aviation landing gear model, tire dynamics are approximated by global parameters, like the three parameters $(T_{re}, \alpha_{co}, \gamma_{co})$ introduced in sub-section 2.3 of this article.

Such tire parameters are evaluated by means of specific experiments. Tire is mounted in a movable upper head [2], which provides steer motion to tire whereas a moving belt simulates relative motion between ground and tire (figure 9). A force sensing balance is connected to tire in order to measure loads.

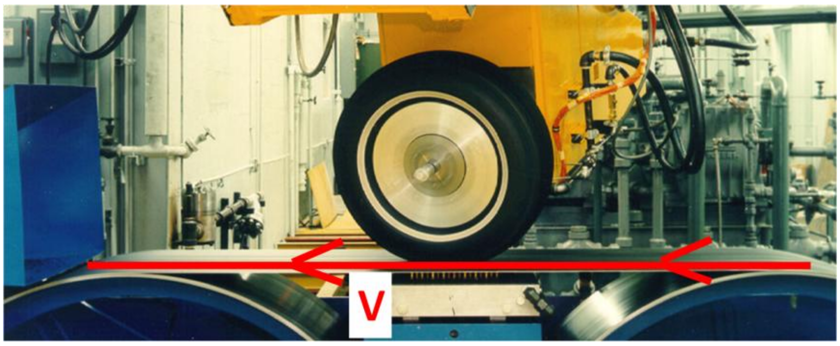

Figure 9: Picture of tire test facility with imposed velocity V (CALSPAN machine)

Similarly to calibration of landing gear structure, post-processing of tire experimental data includes a linearization step required by modal analysis.

The focus is made on determination of the three tire parameters $(T_{re}, \alpha_{co}, \gamma_{co})$ [4] evaluated during Dassault Aviation post-processing (figure 10).

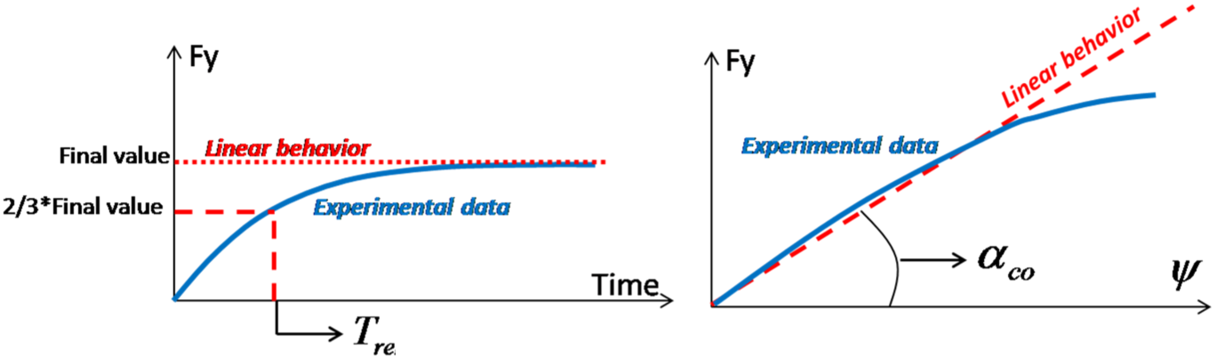

Figure 10: Post-processing of experimental data from tire tests

- To evaluate relaxation time T_{re}, the time evolution of lateral force (going from zero to a non-zero final value) is plotted. The relaxation time corresponds to time for which lateral force reaches two thirds of the final value.
- To evaluate cornering coefficient α_{co}, the lateral force (without taking into account the transition phase) versus the yaw angle is plotted. For the range of interest (angle inferior to a defined level), the evolution is quasi-linear and the slope is cornering coefficient α_{co}.
- The other cornering coefficient γ_{co} is evaluated as α_{co}, just replacing lateral force by torsion moment.

2.5.3 Modal analysis versus time analysis

For both landing gear structure and tire, non-linearities may be taken into account during model calibration if time analysis is used, rather than modal analysis.

Such non-linearities may have a significant influence on landing gear behavior, especially non-linearities of tire. Error of approximation for non-linear parameters due to the linearization process (in addition with other sources of error like experimental dispersion) may have a non-negligible impact on shimmy phenomenon. A sensitivity analysis is required to precisely evaluate this impact. Concerning time analysis for shimmy, approximation level is reduced (no linearization error) but its impact on shimmy analysis is more difficult to evaluate, due to longer delay of simulation and due to non-linear cross-influence of parameters.

Modal and time approaches may be seen as complementary methods.

- Modal approach uses a linear landing gear model, what requires the knowledge of asymptotic behavior. The use of a linear model means a simplification from simulation point of view. Such simplified simulation implies reduced computation times, what makes it possible to perform many simulations required for a sensitivity analysis. Modal analysis only gives information of modes associated with negative damping levels, what means divergent shimmy oscillations.
- Time approach is able to take into account landing gear non-linearities (like friction and free-play). The numerical simulation is then more influenced by experimental data. Time delay of simulation is increased. However, time analysis gives more information about landing gear behavior than modal analysis because amplitude of oscillations is evaluated, what may be relevant in the case of high amplitude for limit cycle oscillations. Moreover, time approach allows a direct comparison of the transient oscillations recorded during a flight operation, contrary to modal approach.

3 APPLICATION OF SHIMMY IN AN INDUSTRIAL CONTEXT

3.1 Presentation of landing gear model

The first step of Dassault Aviation shimmy analysis is the implementation of landing gear model (figure 11).

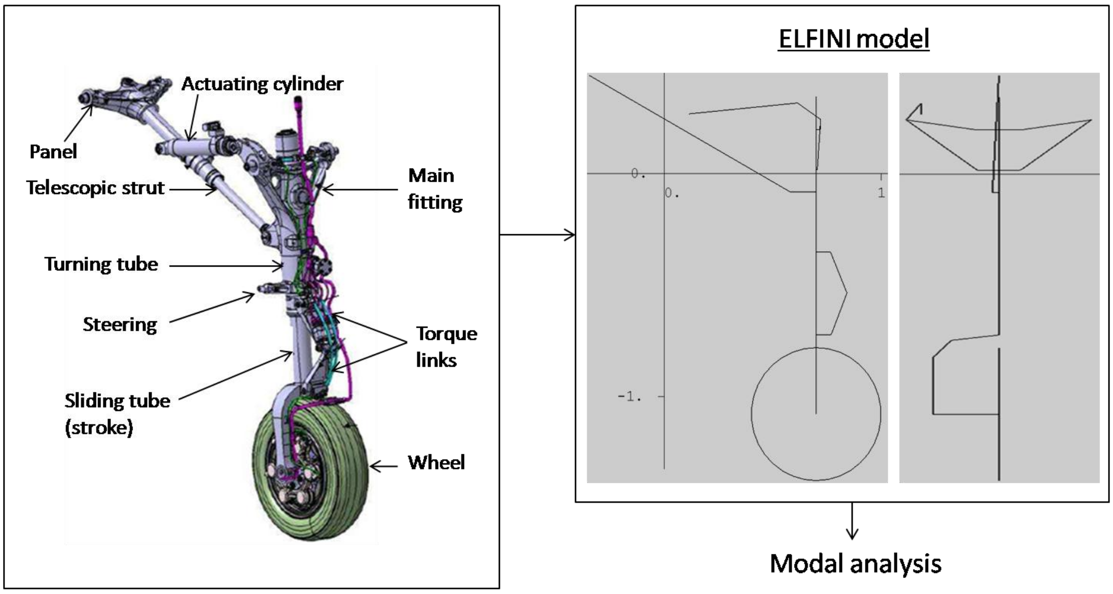

Figure 11: Presentation of a typical ELFINI model of landing gear

The most important sub-elements of landing gear should be identified. In this applicative example, main fitting and telescopic strut linked to the panel are the landing gear elements connected to aircraft. To extend the main fitting, turning tube, sliding tube (controlling the stroke) and wheel are present. Two specific parts are essential to the torsion orientation of landing gear: steering (between turning tube and sliding rod) and torque links (in parallel to sliding rod).

A finite element model of this landing gear is then set up to perform numerical simulations with Dassault Aviation software ELFINI®. This landing gear model is composed of beams and bars whereas sub-models are used to represent specific elements like steering or wheel. Its calibration uses both static and dynamic test data, in addition with specific test data for tire (see sub-section 2.5 of this article).

Before any experiments needed to calibrate landing gear model, structural characteristics (like stiffness or mass repartition) come from the definition of main sub-elements constituting the landing gear. A first shimmy analysis is performed using this preliminary non-calibrated model on a reference configuration associated with a fixed stroke value (figure 12).

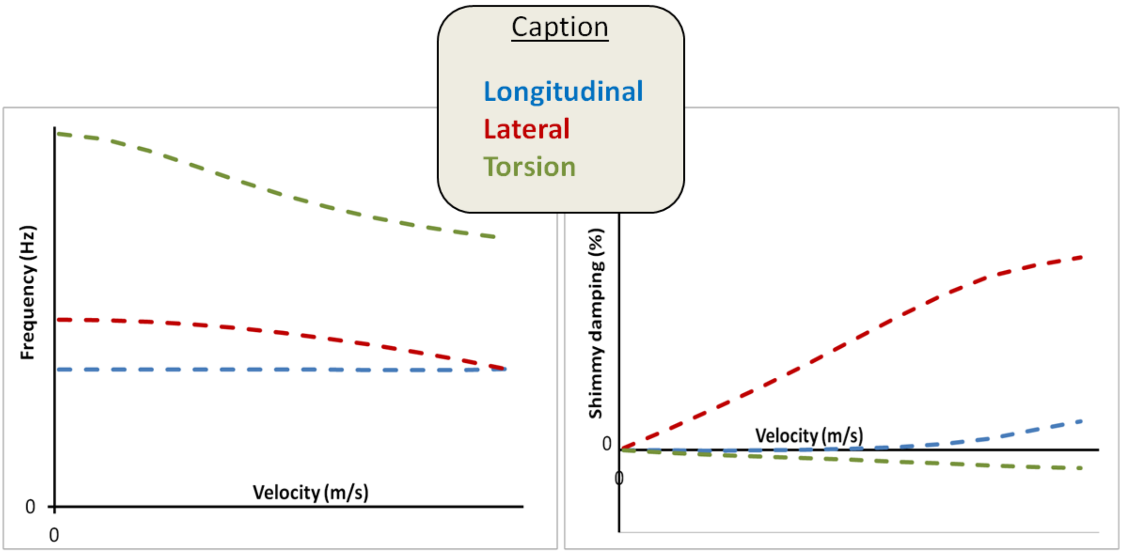

Figure 12: Reference shimmy analysis on a non-calibrated model of landing gear

With these two graphs, the following remarks are made:

- Stability of frequency and damping (despite a slight increase at high velocity) of longitudinal mode means that this mode is not coupled with other modes. Here, only lateral and torsion modes seem to be coupled (variation of frequency and shimmy damping with a variation of velocity).
- A shimmy coupling is observed between lateral and torsion modes. The transfer of energy is going from lateral mode to torsion mode because lateral shimmy damping increases whereas torsion shimmy damping decreases when aircraft velocity increases. Consequently, torsion mode is the potentially unstable mode.

The main objective of shimmy analysis is to evaluate modal response of landing gear rolling on ground, in particular damping levels. Evolution of torsion damping is regular, what is an essential point for the sensitivity analysis. As explained in section 2 of this article, structural damping (conservative estimation) is added to shimmy damping. In this example, total torsion damping becomes positive on the whole velocity domain of variation.

Consequently, no risk of shimmy was first detected by simulation on this non-calibrated landing gear model.

To ensure landing gear stability, a specific analysis supported by dedicated tests may then be set to understand a potential shimmy phenomenon and identify technical solutions.

3.2 Calibration of landing gear model

Several test-campaigns (see section 2.5) may be performed to calibrate landing gear model, composed of static (calibration of stiffness repartition) and dynamic (calibration of mass repartition) tests.

Typical influence of this calibration is summed up in table 1. Absolute relative error associated with the three main natural frequencies (tire not in contact with ground) between non-calibrated and calibrated models is given.

Longitudinal mode	Lateral mode	Torsion mode
15 %	5 %	20 %

Table 1: Absolute relative error of frequency

Calibration of landing gear model has a non-negligible impact on natural frequency (relative error from 5%, up to 20%). Moreover, the maximum error is obtained for torsion mode, which is the potentially unstable mode from shimmy point of view. Such observations confirm that impact of calibration on shimmy analysis should be evaluated.

Typical comparison of shimmy behavior between non-calibrated and calibrated models is given by figure 13.

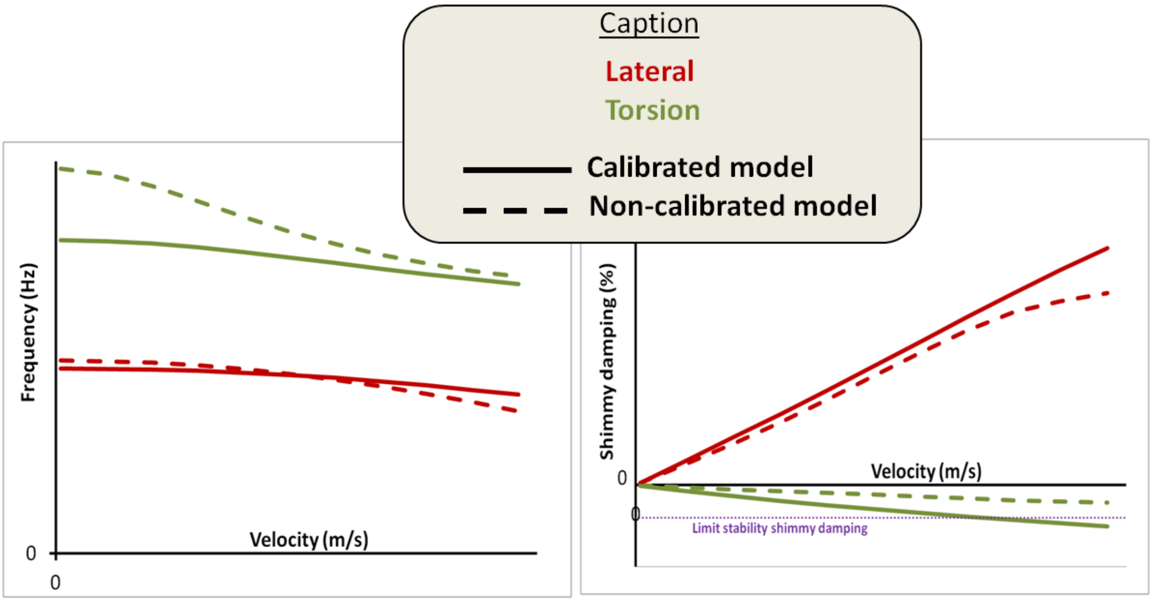

Figure 13: Influence of model calibration on the reference shimmy analysis

Coupling effect between lateral mode and torsion mode remains similar for the two landing gear models (increase of lateral shimmy damping and decrease of torsion shimmy damping when aircraft velocity is increased).

However, the most relevant difference concerns the shimmy damping level of torsion mode which is the potentially unstable mode. Torsion shimmy damping level (due to modes coupling) associated with the calibrated model is inferior to torsion shimmy damping level associated with the non-calibrated model. Damping difference is such that, contrary to the non-calibrated model, the calibrated one demonstrates a shimmy damping inferior to the limit stability value at high aircraft velocity.

This example illustrates the essential role of calibration of landing gear model. It may change conclusions about prediction of shimmy oscillation, going from a conclusion of no shimmy risk to a conclusion of potential shimmy phenomenon.

3.3 Shimmy analysis

To consolidate shimmy analysis, a sensitivity analysis is performed.

The principle of a sensitivity analysis is to measure perturbation of lateral and torsion behaviors in terms of frequency and damping when some parameters are modified. In order to illustrate sensitivity analysis, two parameters are considered (figure 14).

- Stroke value defining the configuration. All representative strokes should be analyzed. Compared with the nominal stroke value linked to the reference configuration, an inferior value and a superior value are considered.
- Tire behavior directly responsible for the apparition of shimmy oscillations. As explained at sub-section 2.5.2 of this article, evaluation of tire parameters $(T_{re}, \alpha_{co}, \gamma_{co})$ is subject to uncertainties (due to linearization operation from experimental data, in addition with other possible sources of error). In this context, shimmy analyses with modified tire parameters are needed to be conservative. The illustration focuses on a variation of $\pm 30\%$ for the two cornering coefficients $(\alpha_{co}, \gamma_{co})$.

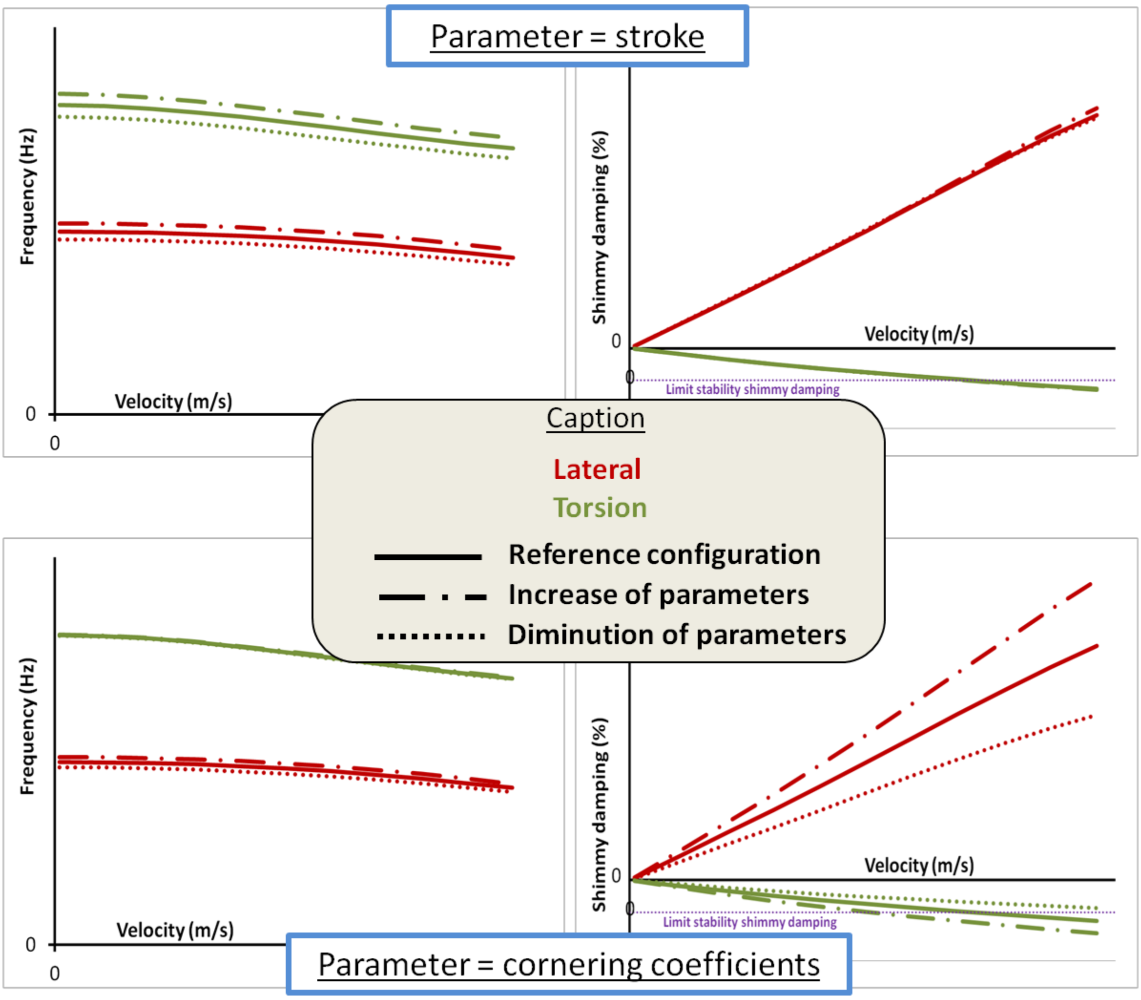

Figure 14: Sensitivity shimmy analysis

In this example, stroke mainly influences frequencies whereas cornering coefficients mainly influence damping values. However, torsion shimmy damping always keeps a regular evolution.

The main objective of shimmy analysis is to quantify a conservative damping level for all configurations. In this context, the estimation of a conservative structural damping is of great importance as it sets the limit stability shimmy damping value.

3.4 Landing gear design

The main objective of landing gear design is guaranteeing a robust positive damping level for all landing gear modes and for all possible configurations (sensitivity analysis).

In this application, the damping level of torsion mode should be increased. The negative torsion damping value is due to a coupling between lateral and torsion modes. Consequently, the principle of shimmy corrections is to weaken this coupling effect by increasing the gap of frequency for these two modes. Two options are then possible: decreasing lateral frequency or increasing torsion frequency.

- In order to decrease lateral frequency, main fitting, turning tube and/or sliding tube could be softened. Such operation would have an influence on longitudinal mode and would require major modifications of landing gear. Moreover, a frequency decrease could result in a higher gradient of the frequency vs aircraft velocity evolution, and so a potentially more pronounced shimmy phenomenon.

- In order to increase torsion frequency without impacting the two other modes, two solutions are conceivable:
    - A first solution is to stiffen the steering element. However, this is a complex element and only an architectural modification is possible to both stiffen the steering and not downgrade the performance level of landing gear.
    - A second solution consists in stiffening the torque links via a modification of their design and/or material.

The corrective strategy consists in testing first the less complex option (stiffening of torque links). Other options are used only if this option is not sufficient. Figure 15 shows the modal evolution when torque links stiffness is doubled.

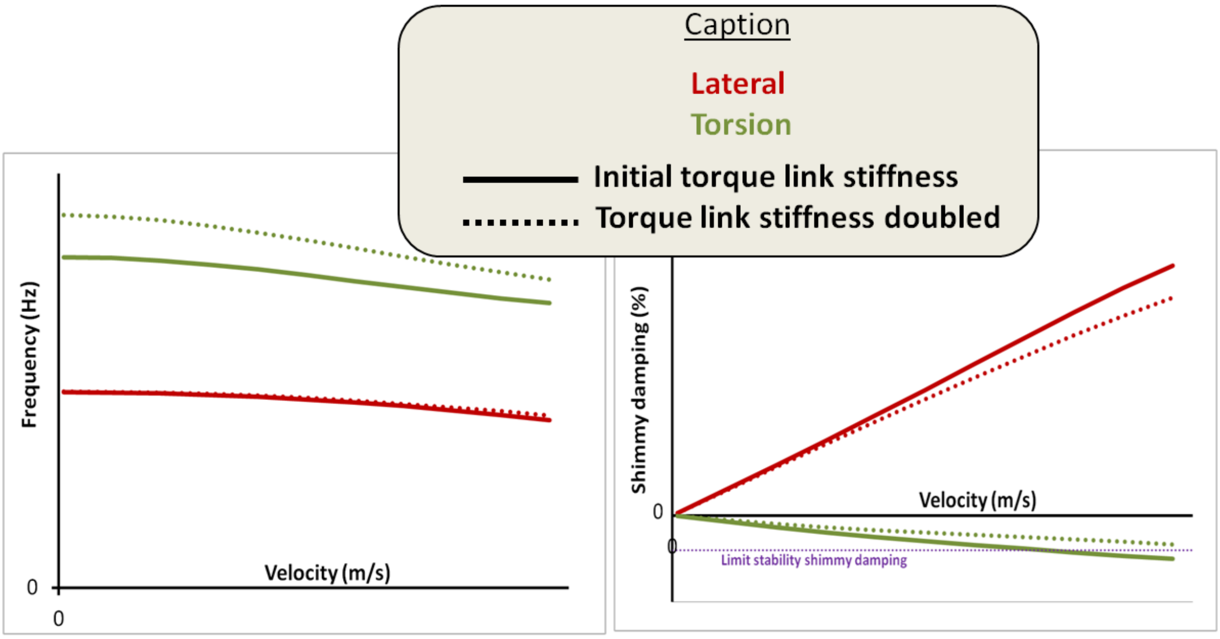

Figure 15: Influence of landing gear modification on shimmy analysis

Considering the increase of torsion shimmy damping when torque links stiffness is doubled, this landing gear modification is sufficient to have a shimmy damping value greater than the estimated limit of stability.

4 LESSONS LEARNED FOR SHIMMY ANALYSIS

4.1 Industrial process

The main lesson learned from typical shimmy analyses described in section 3 of this article is that a landing gear model only based on detailed on-drawing definitions of landing gear sub-elements may be not sufficient to well-predict the shimmy phenomenon. Landing gear is a complex structure which requires specific test campaigns to well-calibrate the finite element landing gear model from the shimmy point of view.

Current Dassault Aviation industrial process integrates **static and dynamic landing gear test campaigns** as an essential step for shimmy analysis.

4.2 Methodology used for shimmy analysis

As explained in previous sections, Dassault Aviation uses rather modal approach to predict the shimmy phenomenon than non-linear time domain approach.

In section 2.5.1, a short comparison is made between this modal approach and another possible approach represented by time approach. These two methods give different information about risk of shimmy apparition.

- Modal approach is able to give an overview of shimmy phenomenon for many possible configurations of landing gear at reduced computational costs. This is an essential aspect, especially when a risk of shimmy oscillations is detected and many conceivable landing gear designs should be evaluated numerically.
- Time approach is a more time consuming method than modal approach, less adapted to guide landing gear elaboration under short deadlines. Compared to modal approach, the main additional contribution of time approach is its ability to integrate non-linear behavior in landing gear model. However, calibration of a non-linear model is challenging in the first steps of landing gear conception. On the other hand, output data from time simulation is more complete than from modal simulation because time information is used to predict not only divergent shimmy oscillations but also limit cycle oscillations. Time approach is also an interesting toolbox to compare transient landing gear behavior between simulations and flight test data.

A way of improvement consists in performing time approach for a few representative configurations, in addition with modal approach used for all other configurations.

When landing gear is conceived to mitigate the risk of shimmy oscillations, the first use of modal analysis is recommended to select some promising architectures. Among these possible architectures, the role of time approach consists in selecting the most adapted one not only to avoid divergent oscillations but also to reduce limit cycle oscillations.

4.3 Calibration of damping level

In the presented application, damping level from numerical simulation is not consolidated by experimental data under flight conditions. Contrary to modal frequencies which are well-estimated with dynamic tests presented in section 2.5.1 of this article, damping levels are more influenced by boundary conditions. Thus, structural damping levels evaluated from such dynamic tests are less reliable to estimate damping levels under flight conditions.

The security margin employed to take into account this uncertainty about damping level may be constraining. In this case, specific experimental tests used to analyze shimmy phenomenon under flight conditions are possible.

The major requirement of such tests is controlling the excitation of landing gear. A lack of control may lead to tests during which landing gear is not correctly excited implying possible false conclusions. Among all possible techniques (use of unbalance masses, obstacles on ground etc), use of pyrotechnics thrusters is considered to be the most adapted method to fulfill this requirement. It consists in hanging pyrotechnics thrusters at each extremity of wheel axle (figure 16). The controlled firing of all thrusters is set up to produce a calibrated excitation of torsion mode, which is typically the potentially unstable mode from shimmy point of view.

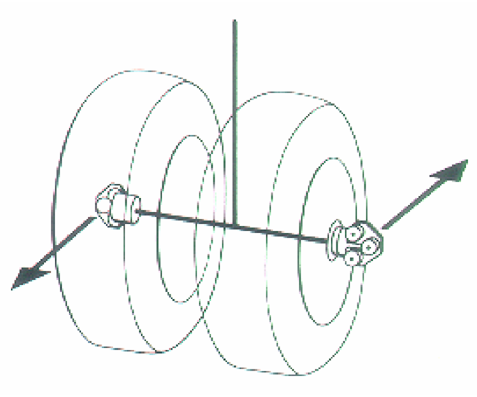

Figure 16: Scheme of pyrotechnics thrusters

A specific instrumentation is devoted to two main tasks.

- Safety is ensured with a control of time evolution of loads applied on landing gear, in order to prevent structural rupture.
- Evolution of landing gear motion after torsion excitation by pyrotechnics thrusters is recorded.

At the end of each test, time evolution of landing gear motion is plotted and analyzed. In particular, damping level associated with torsion mode is deduced from the time evolution of torsion movement of landing gear.

5 CONCLUSION

During taxiing, landing or take off operations of an aircraft, tire/ground contact creates coupling effects between degrees of freedom of landing gear. These coupling influences may give birth to shimmy oscillations, resulting in transfers of energy between landing gear modes. This energy transfer possibly causes instability of landing gear. In order to set up a stable rolling system, numerical simulations are necessary to perform a shimmy analysis. In Dassault Aviation current process, modal approach is used. It consists on an eigenvalue resolution for which the main coupling effects due to landing gear rolling influence are taken into account. A linear model is required for landing gear, implying a linearization operation when experimental data (coming from static and dynamic tests on landing gear structure and from specific tests on tire) are post-processed. Modal approach is able to detect divergent shimmy oscillations. Another possible approach is time simulation, which is a more computer-time consuming method. It allows taking into account structural and tire nonlinear behavior. It gives access to more information about the shimmy phenomenon (limit cycle oscillations, amplitudes etc). Nevertheless, it requires more detailed model data and is more sensitive to calibration.

The industrial application of modal analysis highlights the fundamental role of experimental tests for model calibration. Thanks to this calibration operation, model detects potential risks of shimmy oscillation. Based on the calibrated landing gear model, a modification of the landing gear may be numerically defined and applied.

Some ways of improvement for shimmy analysis may be formulated. The calibration of landing gear model is essential to perform a reliable prediction of shimmy oscillations. Use of both modal approach and time approach gives birth to a process well-adapted to short time delays of industrial context but also able to predict all kinds of shimmy oscillation (from limit cycle to divergent oscillations). In-flight consolidation of the damping level associated with the potentially unstable mode may be required, what implies specific experiments (pyrotechnics thrusters for example).

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