VIBRATION ANALYSIS WITH AN OPTICAL TRACKING SYSTEM (SISTRO)

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ABSTRACT

SisTro validation, required the execution of several Pit Drop tests. The determination of the store trajectory in real time, required the usage of advanced computer vision techniques for photogrammetric measurements and a novel optical calibration and error minimization process. As results the 2D image tracking of the in-view reference points could be determined with sub-pixel resolution. Then, in addition to providing the desired trajectory, it was able to compute the wing and pylon vibrations and its damping coefficient. Such capability allows us to develop a more accurate CFD simulation models by the incorporation of the aircraft Flexible-Body Mechanics model into such simulation runs. In this paper it will be presented the development of SisTrO sub-pixel tracking process and the pit drop test results, that includes the measurement of the wing and pylon vibrations and its associated damping.

INTRODUCTION

Since 2009, the Brazilian Instituto de Pesquisas e Ensaios em Voo (IPEV - Flight Test and Research Institute) is pursuing the objective to develop a real-time solution for the determination of Time-Space Position Information (TSPI) in external stores separation flight test campaigns.

Such novel capability would allow us to move from 1 (one) separation every two days, by using traditional hi-speed cameras with real-time recording and post mission analysis, to up to 2 separations into the same test flight.

The first step, was the development and validation of a computer vision application for the determination of the aircraft altitude in air data system calibration flight test campaign using a single frame [1].

In 2013 the SisTrO development project was started, the basic idea was to embed the tracking algorithm into a hi-speed camera FPGA processor, therefore creating a “smart camera”. For the preliminary evaluation, the developed tracking algorithm was integrated into an iOS mobile device [2], whose camera is not hi-speed, just to measure the performance gain by removing the data transportation process between the camera and the processor and test results were considered satisfactory.

The introduction of the CoaXPress (CXP) protocol Version 1.1.1 [3] providing up to 6.25 Gbps (i.e. CXP-6) per cable for video downlink, removed the data transport bottleneck and therefore it became possible to use a camera connected to a processor for real-time image processing applications.

Nowadays the Japan Industrial Imaging Association (JIIA) is about to release the CXP Version 2 Standard, that provides up to 12.5 Gbps per link (i.e. CXP-12) and up to 50Gbps (i.e. 4 x CXP-12) total. CXP-6 established new grounds for SisTrO development and validation. So, all software components were developed and validated and SisTrO architecture was proposed to allow the determination of the store separation trajectory in real-time.

Among SisTrO components, there is an application that identifies and tracks the 2-D pixel coordinates of all in-view Reference Points (RP). The developed routine was able to measure the RP location with sub-pixel resolution and therefore to identify the aircraft structural flexibility, so wing and pylon vibrations could be properly measured during the Pit Drop tests.

The incorporation of this additional capability by SisTrO will provide relevant information for the development and validation of new and more accurate CFD models where both aeroelasticity and aerodynamical effects will be considered by the CFD model.

STORE SEPARATION FLIGHT TEST CAMPAIGN

The main objective of the store separation Flight Test Campaign (FTC) is to verify if the store could be safely ejected within the aircraft operational envelope. Such verification requires the execution of Computer Fluid-Dynamics (CFD) simulation runs and/or wind tunnel tests.

Parameter identification of the used CFD model, its tuning and the determination of its confidence (i.e. accuracy and uncertainty), requires the usage of several true-reference test flight separation trajectories. During the execution of this FTC, the estimation of the safety level of the next test point, could be accomplished by the correlation of the actual separation trajectory against the associated CFD or wind tunnel information.

Whereas both trajectories are the same, it’s possible to confirm the CFD model accuracy and that the next separation is to be considered safe. Otherwise, in the case of divergence, the CFD model should be refined and improved.

To carry-out such FTC it would be required the usage of the following elements (Figure 1):

1. An optical tracking system (e.g. SisTrO), for the determination of the true-reference separation trajectory;
2. CFD simulation tools and models, for the determination of the estimated separations path; and
3. A trajectory correlation application, for the fitness computation between real and estimation outcomes.

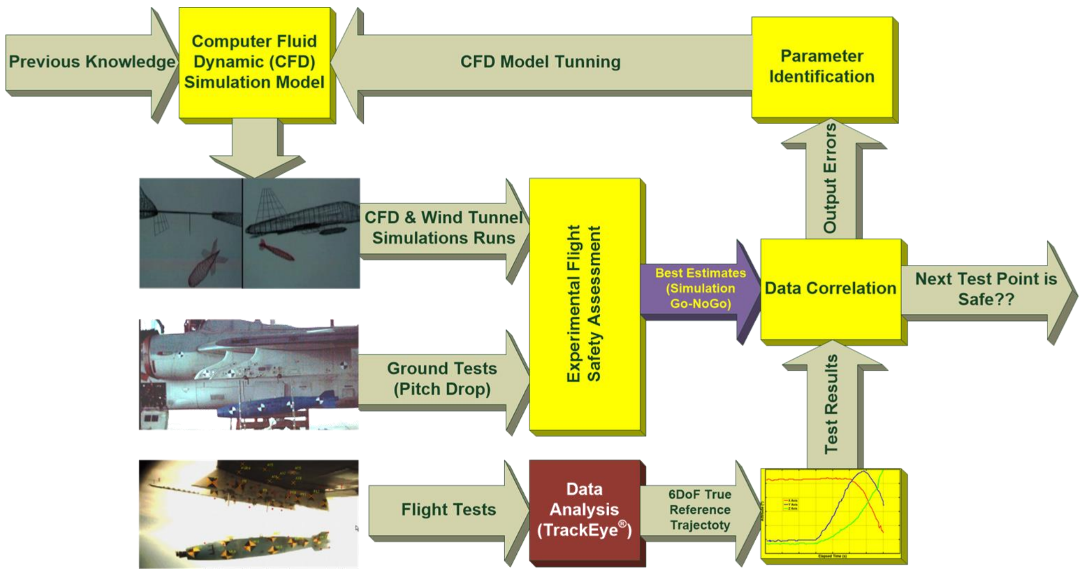

Figure 1 - Store Separation FTC Data Analysis & Test Point Validation

The integration of an optical tracking system, requires the usage of at least two airborne hi-speed, hi-resolution cameras mounted in a fixed-site. Most of the Custom Off-The-Shelf (COTS) cameras used, could only record image frames in real-time, therefore the 3-D trajectory determination and its correlation with the CFD results are executed as post mission operation and such process allows the execution of a single test point per flight, which makes the entire process ineffective.

As a possible solution, SisTrO was designed for improving separation FTC efficiency without jeopardizing its safety levels. The introduction of this system will allow the:

1. Determination of the 3-D separation trajectory in real-time into the test bed;
2. Correlation analysis between the true-reference and CFD estimated trajectories in near real-time into Ground Telemetry System (GTS); and
3. Decision if the next test point should be executed or not (i.e. Go-no-go), to allow the execution of multiple separations in a single flight.

In real-time and for the determination of the 3-D separation path, SisTrO should:

1. Acquire and store the separation 10-bit RGB color image frames in 720p resolution @ 400 fps;
2. Locate and track the 2-D coordinates of all visible Reference Points (RP);
3. Minimize the systematic optical distortion errors in the 2-D coordinates of tracked RP;
4. Compute and store the 3-D coordinates of the in-view RP;

5. Compute the store 6DoF trajectory and send the results to the Airborne Data Acquisition System (DAS) so, separation TSPI, could be merged with the Flight Test Instrumentation (FTI) data set; and
6. Send FTI data to the GTS over the Telemetry Link.

Then in near- real-time operation at GTS a software tool should be used for correlation of the estimated trajectory with its actual path, so the ground crew could decide if the next separation could be safely executed or not.

To aggravate the problem, for simplification most of CFD models are designed to take into account the Flight Mechanics effects (i.e. Rigid-Body to Aerodynamics Interactions), so in many cases the estimated trajectory could be not so accurate. In addition, the increasing usage of composite materials in advanced aircraft, results in more flexible structures, so the separation CFD models should also include Flexible-Body Mechanics and Aeroelasticity effects (Figure 2). In consequence FTI parameter set for store separation FTC should include vibration information.

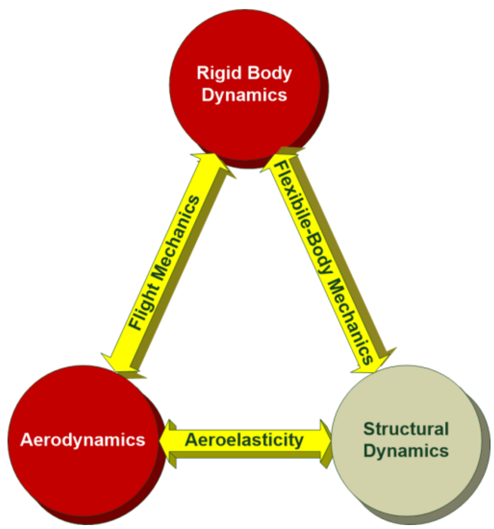

Figure 2 - CFD Modelling in More Flexible Aircraft.

SisTrO ARCHITECTURE

The SisTrO architecture (Figure 3) is composed by the following components:

- ✓ Airborne hi-speed hi-resolution video cameras with 2xCXP-6 down connection channels, totalling up to 12.5Gbps download rate;
- ✓ Image processors, that includes:
  - A dual CXP-6 down connection channels frame grabber; and
  - An IRIG-B time code reader interface.
- ✓ Trajectory processor; and
- ✓ An ETHERNET switch, with:
  - PTP v.2 grand master;
  - IRIG-B/GPS time code generator/reader; and
  - PCM output.

Most of SisTrO components are compliant with MIL-STD-810-F/G and capable to operate within extended temperature range from -40ºC to + 85ºC (i.e. -40ºF to + 185ºF).

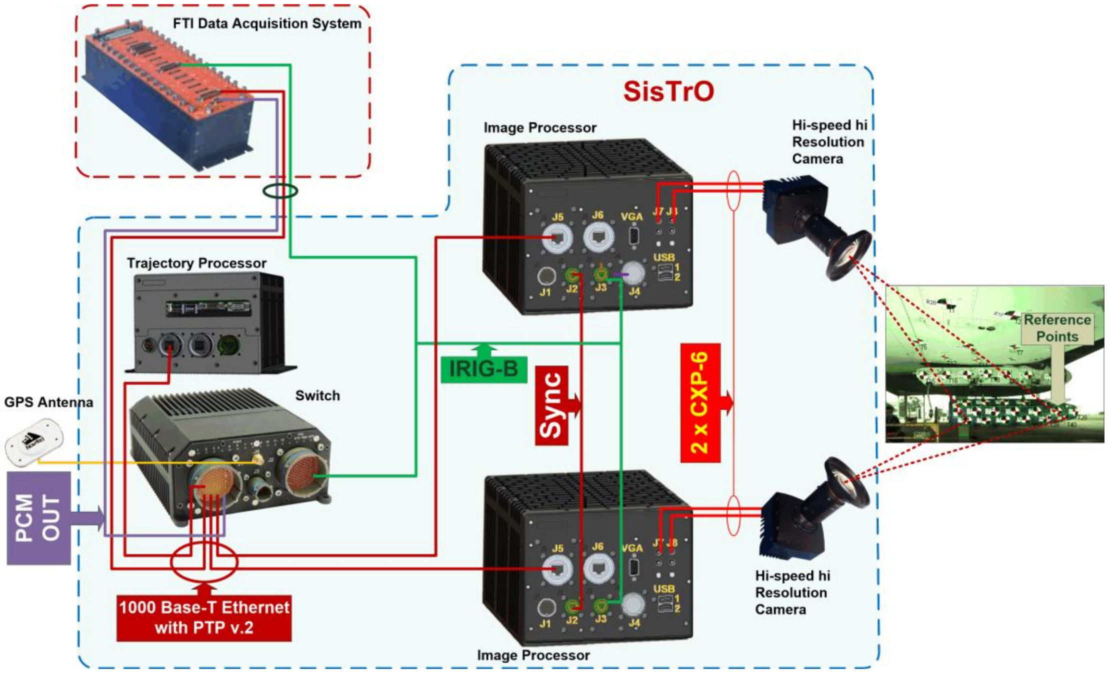

Figure 3 - SisTrO Architecture and Components.

TARGET IDENTIFICATION & TRACKING

The process for target identification and tracking is divided into two parts:

1. Algorithm training; and
2. Object identification.

At the training, images are segmented in several regions of interest, that may contain the sought target image. Then it would be possible to classify such segments as positive or negative samples. As example figure 4 depicts several targets positive image segment samples used for SisTrO development.

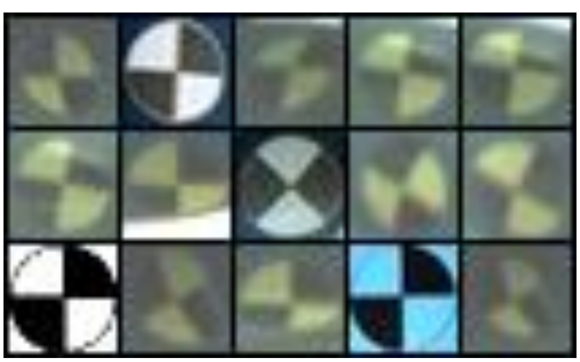
Figure 4: Target positive segment samples images

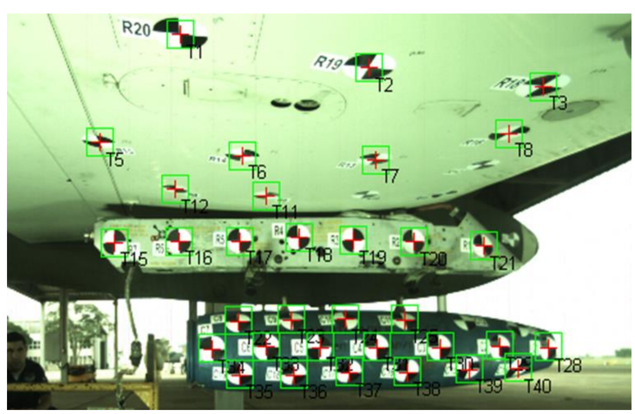
Figure 5: SisTrO RP marker detection and tracking.

Object identification uses a C++ application with OpenCV support, so each image frame is converted to grey scale and its resulting histogram is properly equalized, to enhance image contrast. Then the desired target object is detected and identified as markers. Test runs shows satisfactory results of up to 40 target detection from a single image frame (Figure 5).

Then it would be possible to find the 2-D pixel coordinates of all in-view Reference Points (RP), defined as the geometrical center of each tracked target.

DETERMINATION OF TARGET RP 2-D COORDINATES

The process of image digitization involves two main steps:

1. Sampling; and
2. Quantization.

Image sampling is achieved by the discretization of the scene in a finite number of points (i.e. pixels). The pixel light intensity is quantized in n-bit levels (e.g. 256 levels for 8-bit/pixel quantization process). Also, the image frames could be sampled in RGB color or Greyscale formats. Therefore, the digital representation of video frames is represented in a sequence of multidimensional matrices where each matrix corresponds to a single image frame sampled at time T_i.

The pixel row and column location of the ith indexed matrix corresponds to its 2-D (i.e. x and y axes) pixel location coordinates. The associated information content of each matrix element is the RGB or Greyscale quantized light intensity. Although a given image frame is represented as a discrete map, the exact location of a given target 2-D RP location can be determined with sub-pixel resolution.

Using as example the digitized image frames of Figure 6:

1. Shapes A and D are represented with odd number of pixels considering its rows and columns (i.e. respectively 9 and 21 pixels). As consequence its geometrical x and y coordinates center could be estimated in position $C_a = \{3.5;3.5\}$ and $C_d = \{8.5;9.5\}$;
2. Shapes B and C have even number of pixels (i.e. respectively 16 and 4 pixels). So its associated geometrical center are located in position $C_b = \{8;3\}$ and $C_c = \{2,8\}$.

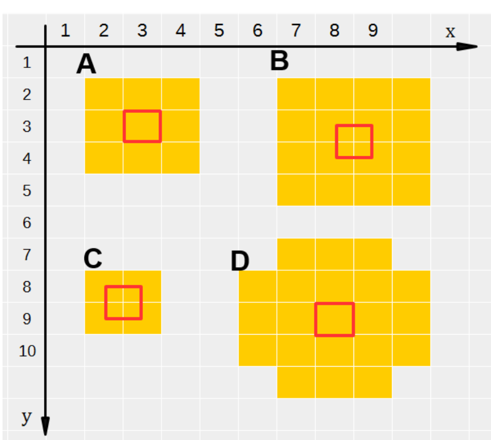

Figure 6: Shapes A, B, C & D image representation

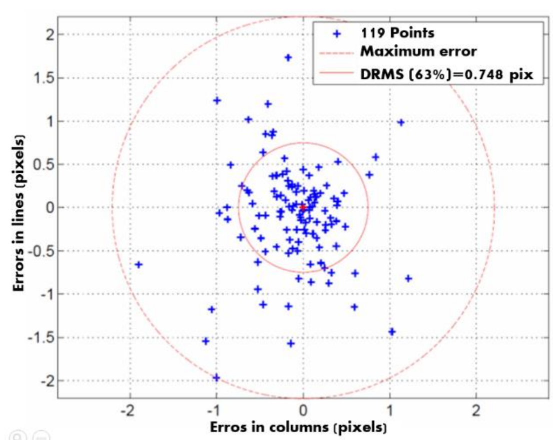

Figure 7: Residual optical errors after calibration.

SisTrO algorithm was designed to locate and track the target edges so, it would be possible to compute is associated geometrical center with subpixel resolution.

SisTrO PRELIMINARY EVALUATION

SisTrO preliminary evaluation was addressed by the execution of several pit drop tests, where a real external store is released in a fixed site. The execution of these trials requires the definition of a unique reference system (S_r), so all local measurements could be properly computed and transformed. So, to accomplish that it was required the:

1. Execution of aircraft levelling procedure;
2. Determination of the 3-D local coordinates of all target reference points (in and out of view);
3. Determination of both camera orientation; and
4. Execution of an optical calibration procedure to minimize camera systematic errors.

The aircraft levelling and the determination of 3-D coordinated of store and aircraft target reference points and camera orientation, was performed with a Theodolite and a Total Station.

Then using a 3-D optical calibration procedure, it was possible to estimate the coefficients of the optical distortion model to minimize most of systematic errors (Figure 7).

Figure 8: Camera POD installed under wing of the XAT-26 aircraft.

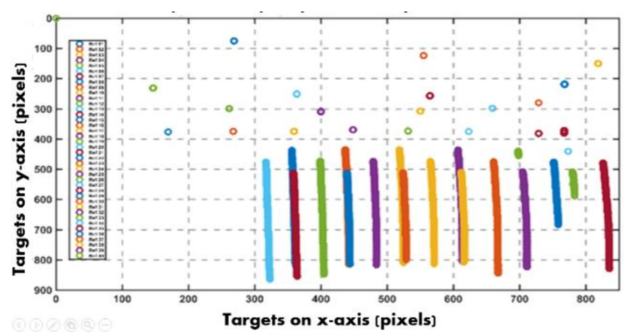

Figure 5: 2D separation trajectory measured by the rear camera.

The pit drop test was executed using as test bed the EMBRAER XAT-26 aircraft equipped with a photographic camera POD (Figure 8) that was installed under wing and carrying an inert exercise bomb.

Test results demonstrates that SisTrO can properly track all in-view target RP's (Figure 9). As consequence with SisTrO it was possible to compute the store linear and angular (Figure 10) components of the 6-DoF trajectory in real time.

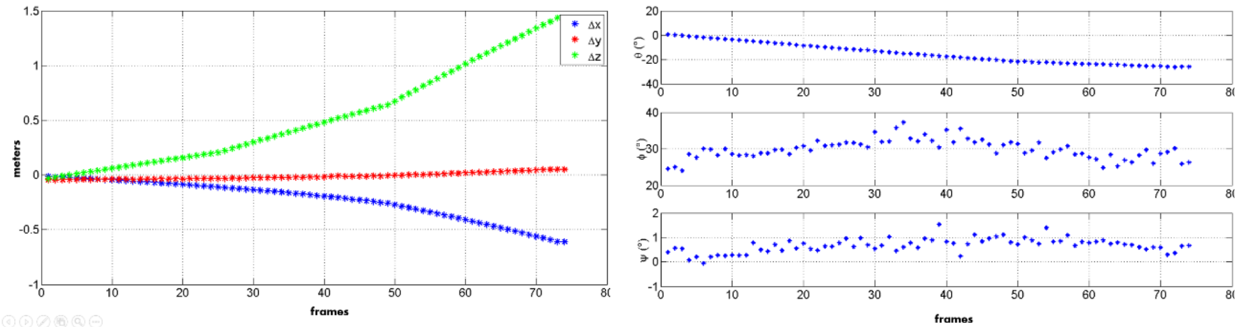

Figure 10: 6DoF Separation Trajectory: a) Linear displacement; b) Angular displacement.

Looking closer to the store ejection point, it is possible to verify that the z-axes target RP path trajectory ($z_i(t_j)$) uncertainty and resolution could actually reach sub-pixel performance (Figure 11). For this analysis:

- ✓ $z_i(t_k) = z_i(t_k) - z_i(t_0)$, where:
  - ○ $z_i(t_k)$ is the pixel z-axes coordinates of the i^{th} target RP at time (t = k); and
  - ○ $z_i(t_0)$ is the pixel z-axes coordinates of the i^{th} target RP at time (t = 0).

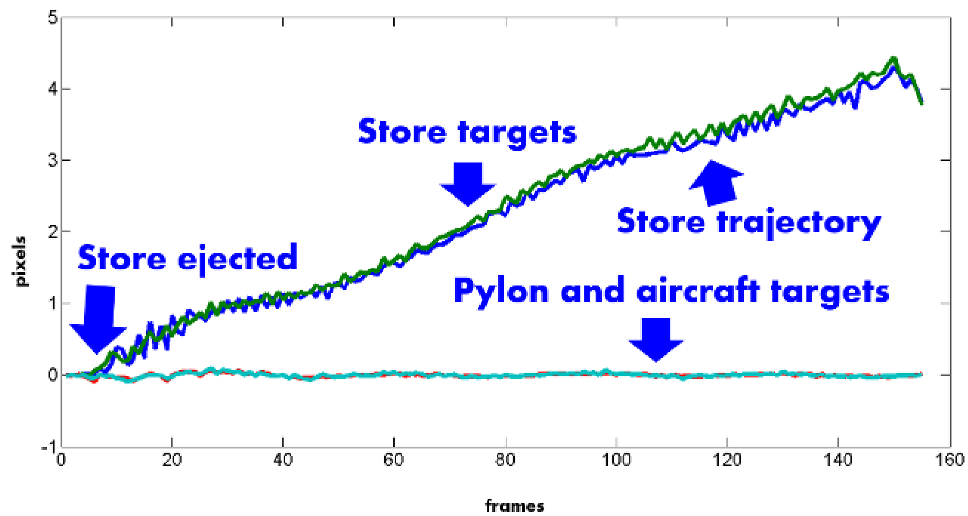

Figure 10: z-axes target RP path

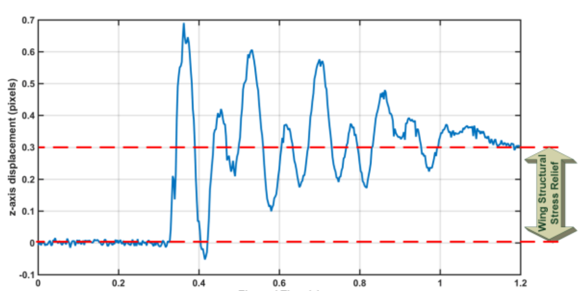

Figure 12: Wing structure vibration & deformation

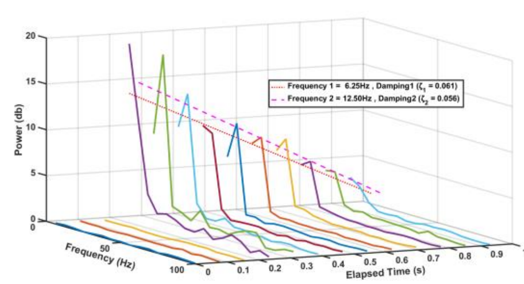

Figure 13: Wing vibration modal analysis results

Furthermore, a detailed time-domain analysis of wing target positioning revealed SisTrO capability to properly sense wing structural vibrations components and the final structure deformation (Figure 12).

Using wing vibration information, it was possible to execute a frequency-domain modal analysis to compute vibration frequencies (i.e. F_1 = 6.25 and F_2 = 12.50 Hz) and its associated damping factor (i.e. ζ_1 = 0.061 and ζ_2 = 0.056), as depicted in Figure 13.

CONCLUSION

SisTrO development provides a new flight test tool where the separation trajectory will be computed in real time by the Photogrametric POD and transmitted to the Telemetry Ground System, for near real-time analysis. So, in near future it would be possible to correlate pre mission CFD simulation results with actual Flight Test ones.

Such novel feature will be the basic grounds for the development and validation of a new decision aid tool, so the confirmation of the CFD model accuracy could be executed during the test flight and therefore allowing the execution of multiple separations into the same test flight, without jeopardizing test safety levels or TSPI accuracy.

The additional SisTrO capability to gather aeroelastic vibration information provides a simple and robust data source for improving CFD model by the incorporation of the aircraft structural dynamics effects into such simulation models.

As next steps:

1. The frequency-domain analysis process should be replaced by a more exact one by using a Gauss-Newton or Least-Squares system identification algorithm, where it would be developed the theoretic vibration model so its parameters could be properly identified for the best-fit results (i.e. minimization of the output errors).
2. Also, it would be necessary to execute more pit drop tests for the investigation if SisTrO could sense other vibration modes (e.g. wing torsion);
3. Then at the end it would be necessary to execute a flutter flight test campaign with SisTrO for validation of this new feature.

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