INTERNATIONAL ADAMS USER CONFERENCE,
ORLANDO, JUNE 19-21, 2000

AIRCRAFT FLIGHT CONTROL SYSTEM MODELLING - CABLE CONSTRUCTION KIT -

François R. Godin *

* BOMBARDIER AEROSPACE INC, CANADA
systems simulation design engineering
technical group leader: antonio d'amore
email: francois.godin@eng.canadair.ca

1 INTRODUCTION

The rapid expansion of the aerospace business in a highly competitive market has prompted a growing usage of computer simulation in support of the design process to reduce cycle time, technical risk, and minimize the costs of rig or field testing.

Aircraft flight control systems is one of the areas in BOMBARDIER where the ADAMS mechanical simulation software has fully integrated the design process. The aircraft' stability and maneuverability are highly dependant on an accurate and reliable flight control system. ADAMS enables the creation of virtual prototypes to assess the system performance throughout the operational envelope and ensure aircraft safety in the event of failures.

A typical powered aileron flight control system is shown in Figure 1; the pilot command is transmitted via a cable system to the actuation devices that move the control surfaces. Aircraft cables make an efficient means for the transmission of control loads over long distances. Their properties however induce many special considerations which have to be taken in account in the overall design of a flight control system.

This paper describes the use of ADAMS customization to automate the creation and facilitate the management of cable systems; a major player within flight control systems.

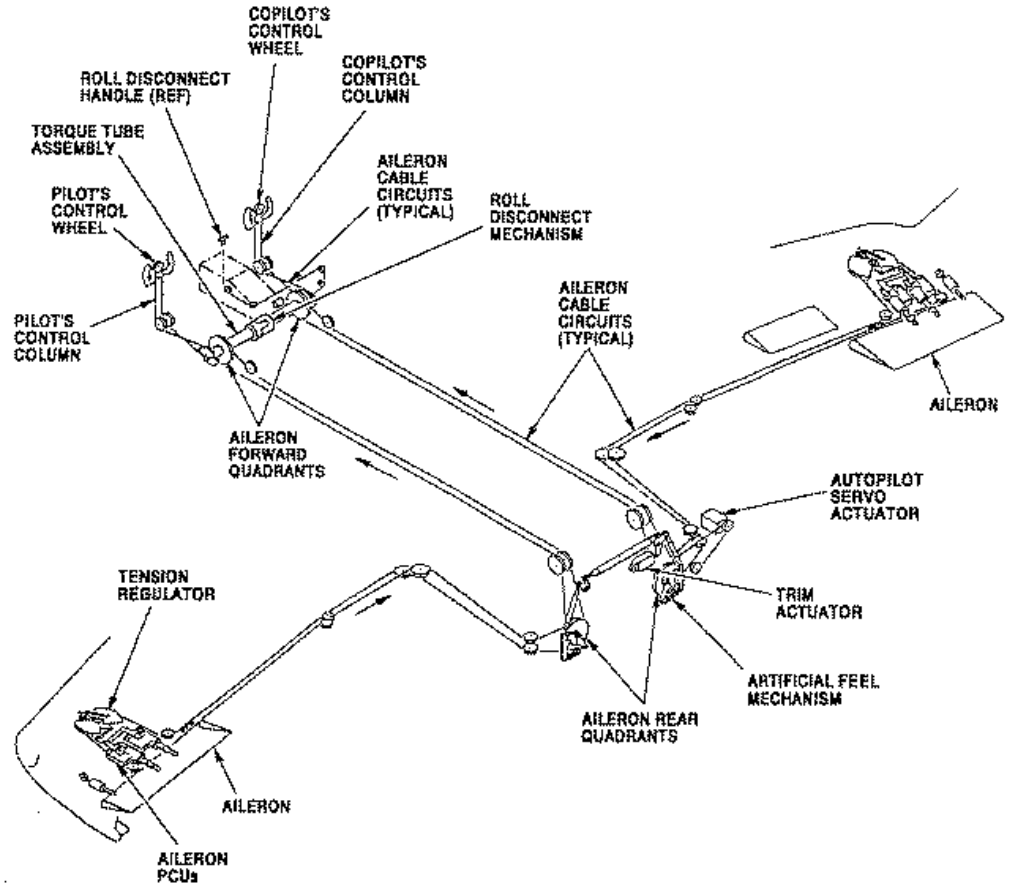


FIGURE 1 Typical Cable Flight Control System

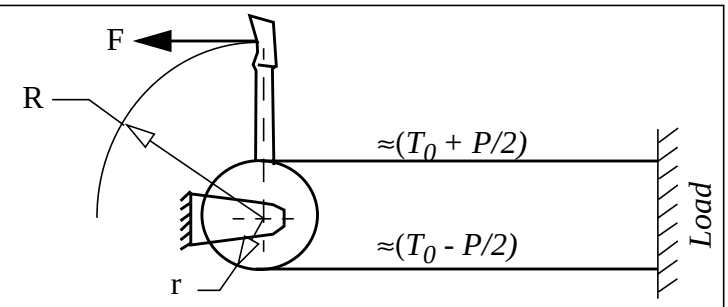
2 THEORY OF CABLE MODELLING

Depending on the required degree of accuracy, various techniques can be used to model a cable system. A very simple method consists of the use of coupler joints to model infinitely stiff cables. This may be sufficient when the analysis does not require the need to study the effect of cable stretch. At the other extreme, a cable could be discretized into a chain of small cable elements, connected together with springs or bushings, using impact statements to simulate the contact with the pulleys. The latter however may not be well suited for large cable systems and will quickly raise the level of complexity of the model.

The technique described here attempts to model only the effects of the cables on the other parts of the system. Cables are represented by non-linear springs applied tangentially on the pulley. Figure 2 shows the calculation of cable deflection for a simple cable layout.

$$\delta_c = \frac{(P \bullet L \bullet K_I)}{2 \bullet E_c \bullet A_c}$$

for P/2 < T_0



δ_c = cable extension or contraction between supports due to load application [in]
L = cable effective length [in]
P = cable load equivalent to pilot's effort [lb]; $P = F \bullet \left(\frac{R}{r}\right)$
E_c*A_c = Primary modulus for wire rope
K_I = installation rigidity factor (allowance for deflection of quadrant and pulley attachments; usually in the range of 1.2 to 1.4).
T_0 = cable rigging preload [lb]

FIGURE 2 Cable deflection with a rig load

The primary modulus (EA) of the cable accounts for both the material elasticity and the stiffness of the cable construction. This constructional stiffness increases with load making the cable characteristics non-linear. The EA values represent the slope of the load versus unit deflection curves usually established by tests. These curves can be obtained from the cable manufacturers and often encompass wide tolerance bands. Figure 3 shows the characteristics of a typical wire rope used in flight control systems; 1/8" diameter 7x19 stainless steel cable.

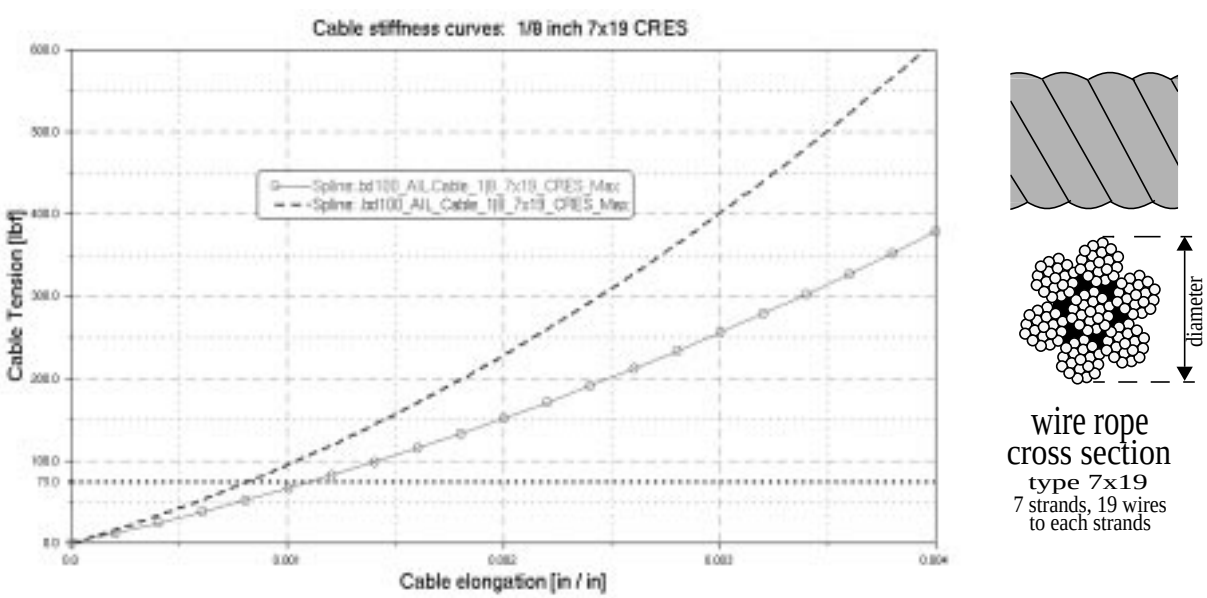


FIGURE 3 Cable stiffness curves: 1/8 inch 7x19 CRES

Closed loop flight control cable systems are rigged to a predetermined preload that keeps the cable in tension and minimizes system backlash. The rig load also eliminates approximately 50% of the cable deflections caused by the operating loads because the load is divided between both sides of the input quadrant (Figure 2). Without preload, one side would go slack and the effective stiffness of the circuit would drop by half.

The level of rig load can change with flight conditions from it's preset value :

- *Differential thermal expansion/contraction between cable and the aircraft structure.* In the aircraft wing and empennage, both the structure and cables can be assumed to stabilize to the same temperature, however large temperature differences exists between the steel cables running through the warm pressurized sections of the fuselage and the aluminium structure at the low sub-zero temperature of high altitudes.
- *Cabin pressurization effects.* Cable preload value will raise when the cabin is pressurized due to fuselage length increase.
- *Structure deflection.* If the cable path is not located on the neutral bending and torsional axes of the aircraft and wings, the structural deflections will affect the cable preload.

For these reasons, precaution must be taken when calculating the cable system preload to prevent the return cable from going slack under operating conditions.

Another important characteristic of flight control cables is their significant contribution to the overall system friction. The importance of low friction in a flight control system can never be stressed enough; the handling qualities of an otherwise excellent airplane can become completely unacceptable due to excessive friction. Cable friction results from the rubbing of the individual wires when the cable deforms and works as it bends over a pulley or fairlead. This friction is function of many installation factors including cable to pulley diameter ratio (d/D), cable lubrification, cable preload, cable wrap on the pulley and pulloff angle. The bearings of the pulleys and quadrants along the cable routing also contributes to the cable run total friction.

3 CABLE CONSTRUCTION KIT

A set of macros and dialog boxes have been designed to create parametrized cable run objects. A cable run is defined as a cable section which has both ends rigidly fixed to a quadrant or a lever. The following two types of cable runs are currently supported by the cable construction kit:

- Quadrant to Quadrant cable run
- Lever to Pulley/Quadrant cable run

Flight Control cables are modeled as force spline functions with the cable deformation as the independent variable. Of course, cables may only be loaded in tension, thus slack will occur when the tension in one of the cable drops below zero.

Quadrant to Quadrant cable run

For this type of arrangement, the kit creates two new parts (cable ends) for each cable run on the circumference of the end quadrants (located in polar coordinate r, Θ on the xy-plane of the revolute joint). The local coordinate system of each part is constructed with ***x*** oriented toward the center of the quadrant and the positive ***z*** direction aligned along the cable length (normal to the quadrant radius). These parts are then constrained with a pair of translation and gear joints to couple the translational displacement of the cable end with the quadrant rotation (Figure 4 illustrates the layout for one end of the cable). Single component forces attached on each cable end parts calculate the cable tension as a function of cable installation elongation (preload), length, installation rigidity factor and the relative displacement of the two cable ends.

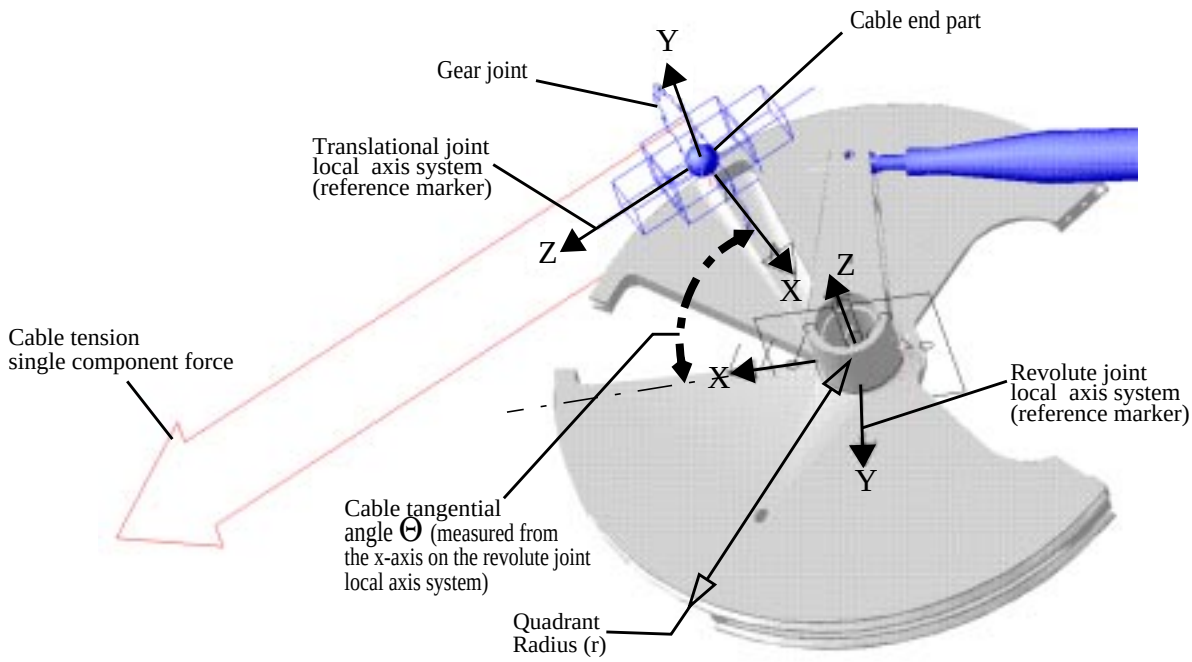


FIGURE 4 Quadrant End General Layout

The kit does not require the two cable ends to be directly connected with a single straight cable length. A virtual (non modelled) cable routing can take place between the two ends resulting in the two cable tension single component forces for the same cable run not being co-linear. The cable tension is assumed equal in magnitude at both end.

As the translational displacement of the cable end part is rigidly coupled (with the gear joint) to the rotation of the revolute it is assumed that no cable slip will occur.

Lever to Pulley/Quadrant cable run

The main difference for this type of cable is that the single component force at the lever attachment will vary both in direction and magnitude. The cable is directly attached to the lever part at one end with the direction being calculated at runtime to stay aligned with the other end cable contact point (Figure 7 illustrates a lever to pulley cable: cable1end). The pulley attachment end is handled the same way than the other type. Naturally, for this type of cable, the two ends must be directly connected with a single straight cable length.

As the lever end rotates, the cable contact point on the pulley will move slightly. The model currently assumes a fixed point of contact. This will result in a small variation of the lever-end force direction. The resulting error was found to be negligible in the analysis that led to this design. The assumption may not be valid for all applications.

Cable Construction Kit Generated Functions

The calculation of the tension is done as follow for the two type of cables. The installation elongation is computed in a design-time expression to account for the static rig load.

<table>
<tr><th>Quadrant <-> Quadrant</th><th colspan="2">Lever <-> Quadrant</th></tr>
<tr><td>$stretch = DZ(\text{endA\_j}, \text{endA\_i}) + DZ(\text{endB\_j}, \text{endB\_i})$</td><td>$stretch = DM(\text{endA\_i}, \text{endB\_j}) - DM(\text{endA\_j}, \text{endB\_j}) + DZ(\text{endB\_j}, \text{endB\_i})$</td><td rowspan="2">(STATE VARIABLES)</td></tr>
<tr><td>$deltaV = VZ(\text{endA\_j}, \text{endA\_i}) + VZ(\text{endB\_j}, \text{endB\_i})$</td><td>$deltaV = VM(\text{endA\_i}, \text{endB\_j}) - VM(\text{endA\_j}, \text{endB\_j}) + VZ(\text{endB\_j}, \text{endB\_i})$</td></tr>
<tr><td colspan="3">$\text{inst\_elong} = VALAT(\text{spline.y}, \text{spline.x}, (preload \cdot \text{inst\_factor}))$
(DESIGN VARIABLE)</td></tr>
<tr><td colspan="3">$tensionEndA = \left(\frac{1}{\text{inst\_factor}}\right) MAX\left(0, AKISPL\left(\left(\left(\frac{VARVAL(stretch)}{\text{cable\_length}}\right) + \text{inst\_elong}\right), 0, spline\right)\right) + VARVAL(deltaV) \cdot \text{damping\_coeff}$
(SINGLE COMPONENT FORCE FUNCTION)</td></tr>
<tr><td colspan="3">$tensionEndB = SFORCE((tentionEndA, 0, 1, \text{EndA\_j}))$
(SINGLE COMPONENT FORCE FUNCTION)</td></tr>
</table>

The cable creation dialog boxes are shown in Figure 5. The only objects required for the creation of a cable are the cable stiffness characteristics spline (see Figure 3) and the revolute joints of the cable end attachments (for the LEVER<->QUADRANT cable type, an attachment marker is also required on the lever part). The other inputs are stored in development variables to enable the parametrization of the cable object. The cable diameter parameter is used to size the cable end parts.

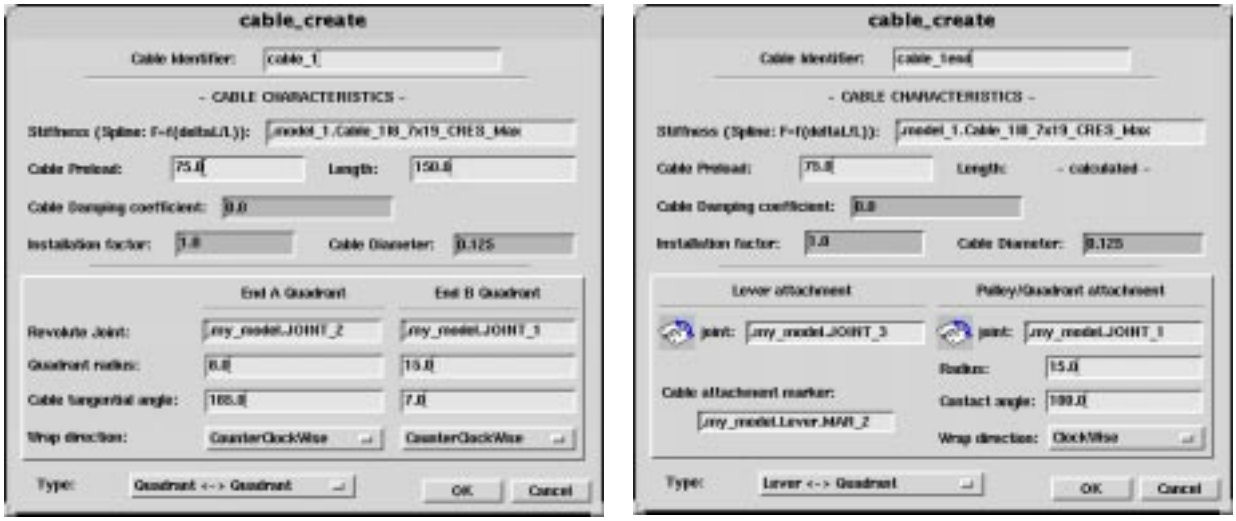


FIGURE 5 Cable Creation Dialog Boxes

The cable objects management is performed through the cable modify dialog box (Figure 6). Except for the revolute joint of the attachments, all the other parameters that defines a cable object may be modified.

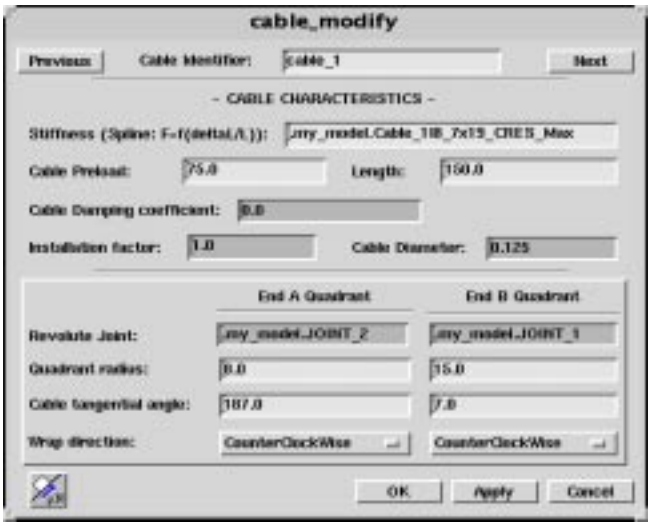


FIGURE 6 Cable Management Dialog Box

Cable friction can be added to a cable run using the friction icon at the bottom of the cable modify dialog box. The friction preload is split evenly into the translation joints at both ends of the cable. Currently the kit only support constant preload friction, care must be taken when performing analysis where the cable tension varies tremendously from the design rig load.

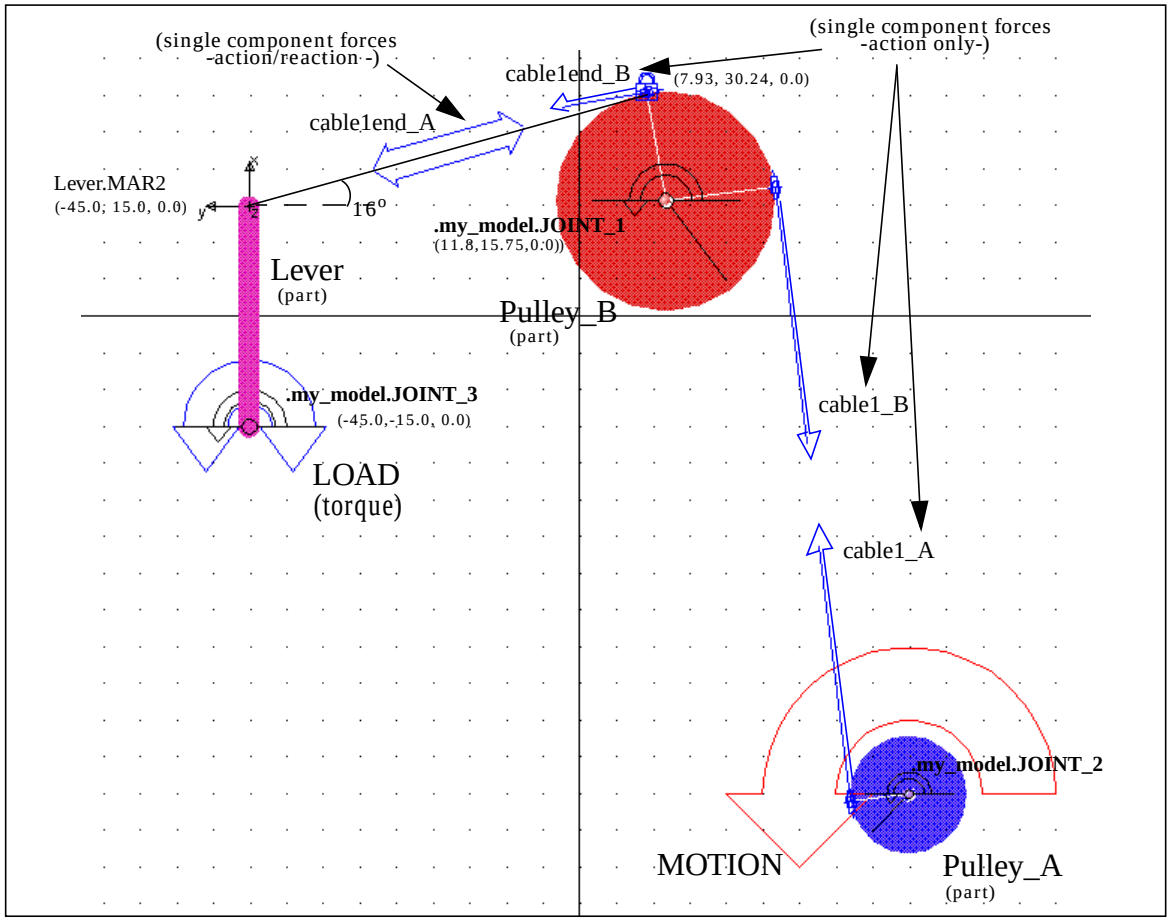


FIGURE 7 Sample model using the two types of cable

Figure 8 shows the results of a simulation of a sample model that consists of an open loop cable system between two pulley and a lever. The displacement of the first pulley is constrained by a motion statement and a resisting torque is applied on the lever rotation axis (stiffness: 50.0 [lb-in/deg], preload: 30.0*75.0*cos(16°) [lb-in]).

As expected. the system initially reaches static equilibrium at the design position with both cable tension at 75 lbs (the torque preload was sized to hold the cable tension at rig load). As the Pulley_A is rotated, the cable pulls on the lever against the load. The total rigid displacement of the Pulley_B for 30.0° motion of Pulley_A would be 16.0°. The actual displacement is 15.85 degrees accounting for cable stretch. The system' performance thus proves to be consistent with analytical predictions.

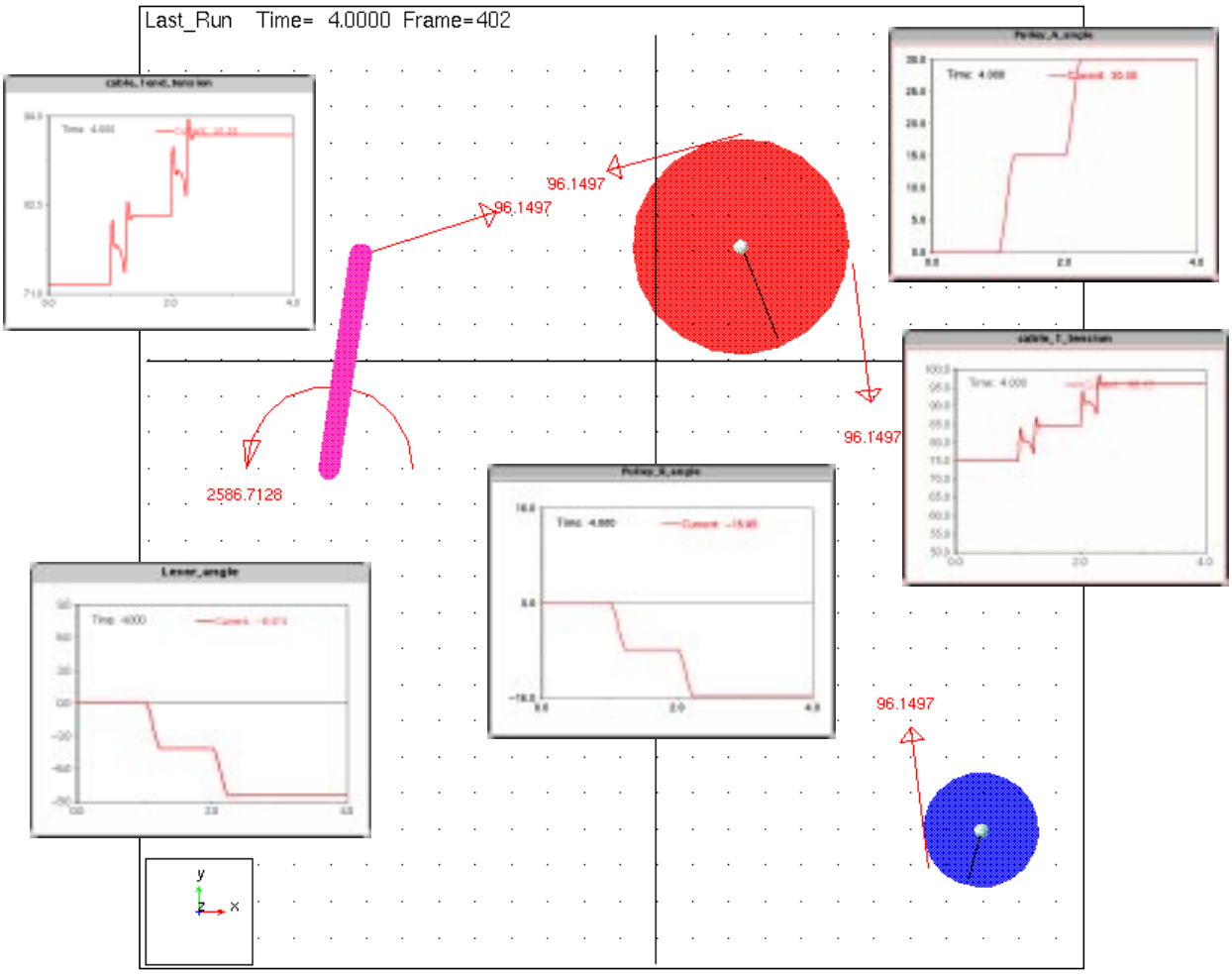


FIGURE 8 Simulation results of a simple cable system

4 CONCLUSIONS

Cable systems created with the cable construction kit are being used within complete ADAMS flight control models to predict the system performance and investigate failure cases on the Bombardier Continental Jet ongoing design program. Various types of analysis require adequate cable models to support the design process of flight control systems:

- Effective system rigidity
- Overall system dynamic response
- Cable snap (transient and steady state effects)
- Verification of the system centering
- ...

Significant time savings have been gained as the manual creation of cable systems is error prone and time consuming. Additionally, parametrization of the cable system allows for quick changes to the cable system properties to do sensitivity study without requiring important model modifications.

The cable construction kit is still in its early stage of development. A “crawl-walk-run” progression, well known to ADAMS model designers, was adopted to fuel the confidence in the behavior fidelity.

Future improvements to the kit could involve the following:

- improve the cable friction computation (function of cable tension)
- account for differential temperature or cabin pressurization effects on the cable rig load
- add a new type of cable: Tension Regulator mounted cable
- simulate cable slip on the pulleys

The kit evolution will be dictated by the need for higher fidelity as the cable modelling effects will be compared to test results.

REFERENCES

[1] BM5003.08, Bombardier Design Manual, Flight Control System

[2] BDM-1606, Boeing Design Manual, Mechanical controls, June 1990

[3] CMS 511-01 Wire Cable for Aircraft Control Systems

[4] MIL-W-83420 Wire Rope, Flexible, for Aircraft Control