Efficient Modeling of Extensible Cables and Pulley Systems in ADAMS^{Ò}

Dr. Andrew S. Elliott
MSC.Professional Services
6530 East Virginia Street
Mesa, Arizona, USA 85215
480.985.1557
andrew.elliott@mscsoftware.com

ABSTRACT

A new method has been developed for accurately and efficiently modeling string-like cable components that change length during an event. String-like components are flexible elements that only support tension loads, not compression nor bending. The method is also applicable to many and various kinds of ropes, tapes, chains and belts. It includes the effects of both variable mass and variable stiffness. A new pulley model, capable of non-planar input and output, has also been developed for connecting such cables (rigid, flexible or extensible) to other parts of a modeled system. This method has been tested on an aircraft carrier arrestment problem which includes significant high and low frequency cable dynamics.

INTRODUCTION

Despite ADAMS impressive general capabilities for mechanical systems modeling, it lacks straightforward methods to model some very basic standard mechanical device components. One of these components is the *cable*, defined in this paper as a string-like element that only supports tension loads, not compression nor bending. This general component class also includes various kinds of fiber and wire ropes, polymer and metal tapes, elastomeric and reinforced belts, and all kinds of chains.

Cable-like components are used in an extraordinarily large group of mechanical devices, from rather simple things like the block-and-tackle, to cranes and elevators, to drive and synchronization systems, even to very complex systems such as the aircraft arresting gear on an aircraft carrier. In some of these applications, the cable dynamics are very low frequency and quite benign, and can be ignored. In many applications however, the cable dynamics, including both axial and transverse waves, are the controlling component for the system loads.

Of course, in order to get useful work from a cable, it is usually necessary to be able to change its direction to route it through a device, and/or to convert linear cable motion to rotary motion to provide power transmission. This is done with *pulleys* (or sheaves), another basic mechanical component that is missing from the core ADAMS modeling repertoire. This device class includes everything from the multitudinous tiny roller guides within a tape drive, to the giant drive wheels in a cable car system.

In the general case, a dynamic pulley model should allow for the cable to wrap and unwrap around the pulley, giving variable entry angles, as well as enter the pulley from slightly out of the pulley disk plane. Of course, cable load must translate to load and torque on the pulley, and partial cable slip should also be possible where appropriate.

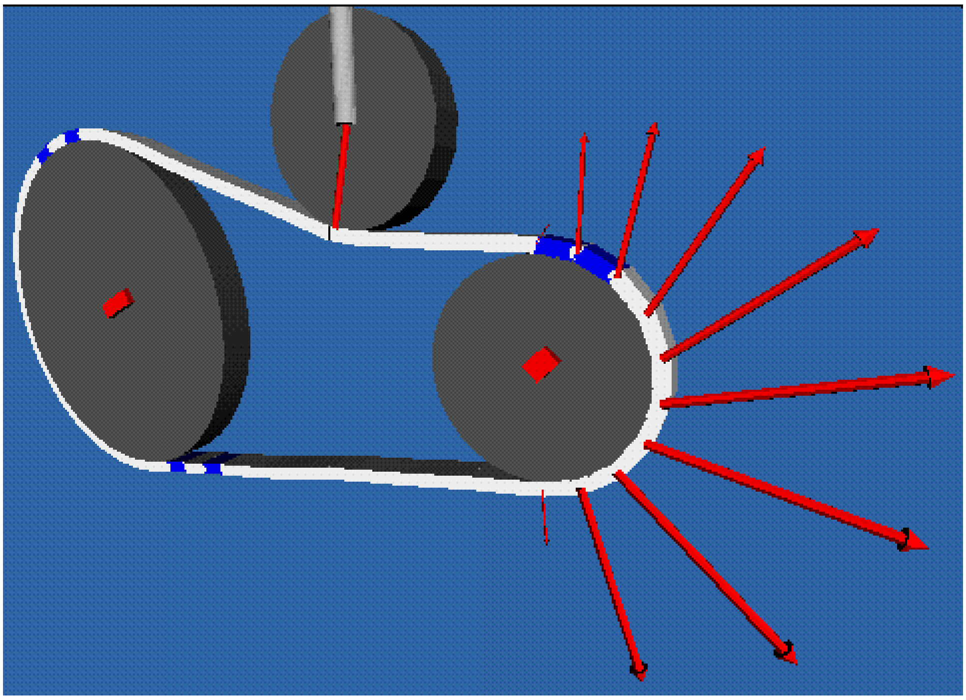
Finally, for certain problems, the cable and pulley models must work together to allow for large amounts of cable to "play out" during the simulation. To avoid having to carry a very large number of cable elements through the simulation, even when they are not active, this requires a special cable element that has variable length and mass characteristics, but otherwise can be used just like a normal fixed-length cable element. This special cable element is the primary development reported in this paper. The type of problems it makes tractable will be treated in more detail below.

MODELING STRATEGIES

LEVEL 1 – The simplest kind of cable/pulley systems are those in which the cable dynamics, i.e. the effects of the actual cable structural response, can be comfortably ignored. This might be the case for a power transmission device which operates at nearly constant tension at very low speeds compared to the cable wave speeds. For this case we can model the cable pseudo-kinematically and concentrate on the pulley part of the system.

LEVEL 2 – The next, more complicated kind of cable/pulley system is one where the cable dynamics and structural response are very important to the overall system response, but in which the base geometry of the system changes very little during the simulation. In this case, we can use a fixed number of flexible cable elements of fixed length.

The best example of this kind of problem would be a chain or belt drive. Unlike the models shown in the Level 1 section, here the belt/chain elements flow continuously through the system, between and around the driving pulleys or gears. This kind of problem has been heavily addressed by various authors at many conferences in recent years. In addition, there are many example applications in the MSC/ADAMS model database. The interested reader is directed to the references.

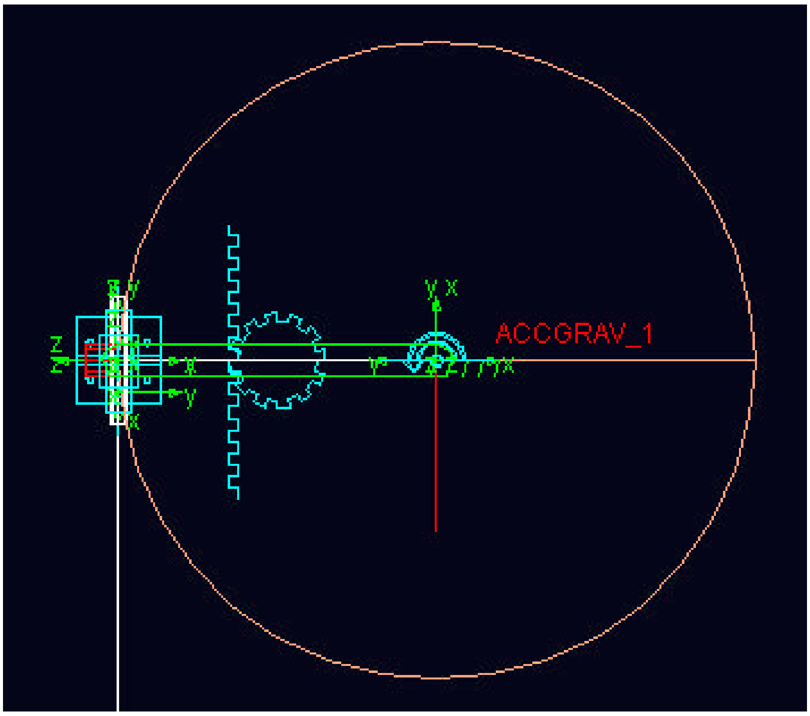


LEVEL 3 – A different, more complicated kind of cable/pulley system is one where cable dynamics are controlling the overall system response, <u>and</u> in which large amounts of cable (greater than 10% of initial length) can be injected into the system during the simulation. Examples of this kind of problem would be drag-line bucket operations, suspended cable car transient motions and, of course, the aircraft carrier arrestment. For Level 3 applications, the puelly can be very similar to the Level 1 approach, and we concentrate on a better cable model.

LEVEL 1 CABLE/PULLEY SYSTEMS

This type of cable/pulley system is characterized by strictly kinematic relationships between input and output pulley motions and by rigid input and output cable sections. Compliance can be inserted between the output of one pulley and the input of another to give the some gross effect of cable stretch.

The Level 1 pulley uses quite a few "dummy" parts to simulate actual cable-pulley interaction. One side of such a pulley is shown here with the joint icons visible:

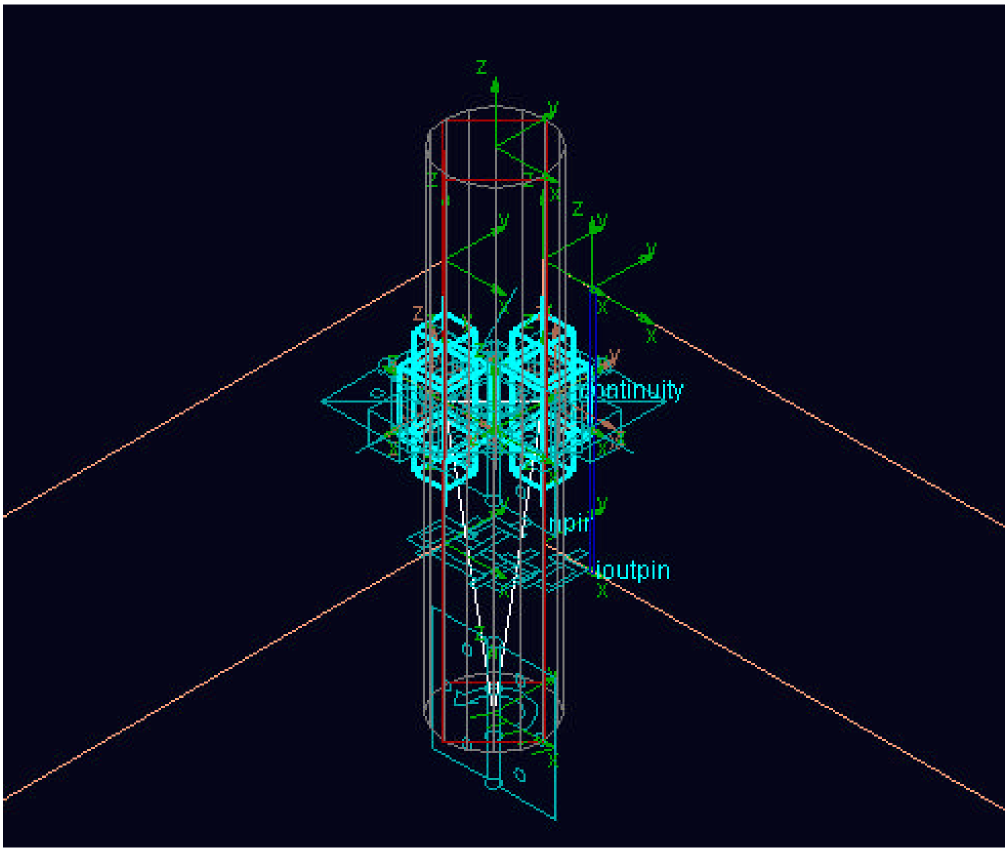


The brown pulley body is connected to the base part with a revolute joint at the center. The first dummy part, shown by the green link, is connected to the pulley body with a coaxial revolute joint, which effectively constrains the cable to stay tangent to the body at all times.

The second dummy part, shown by the hard-to-see short red cylinder, is connected to the first dummy part with another revolute joint oriented radially. This "turret" allows the cable to enter the pulley from out of the pulley body plane and allows construction of realistic devices like the block and tackle.

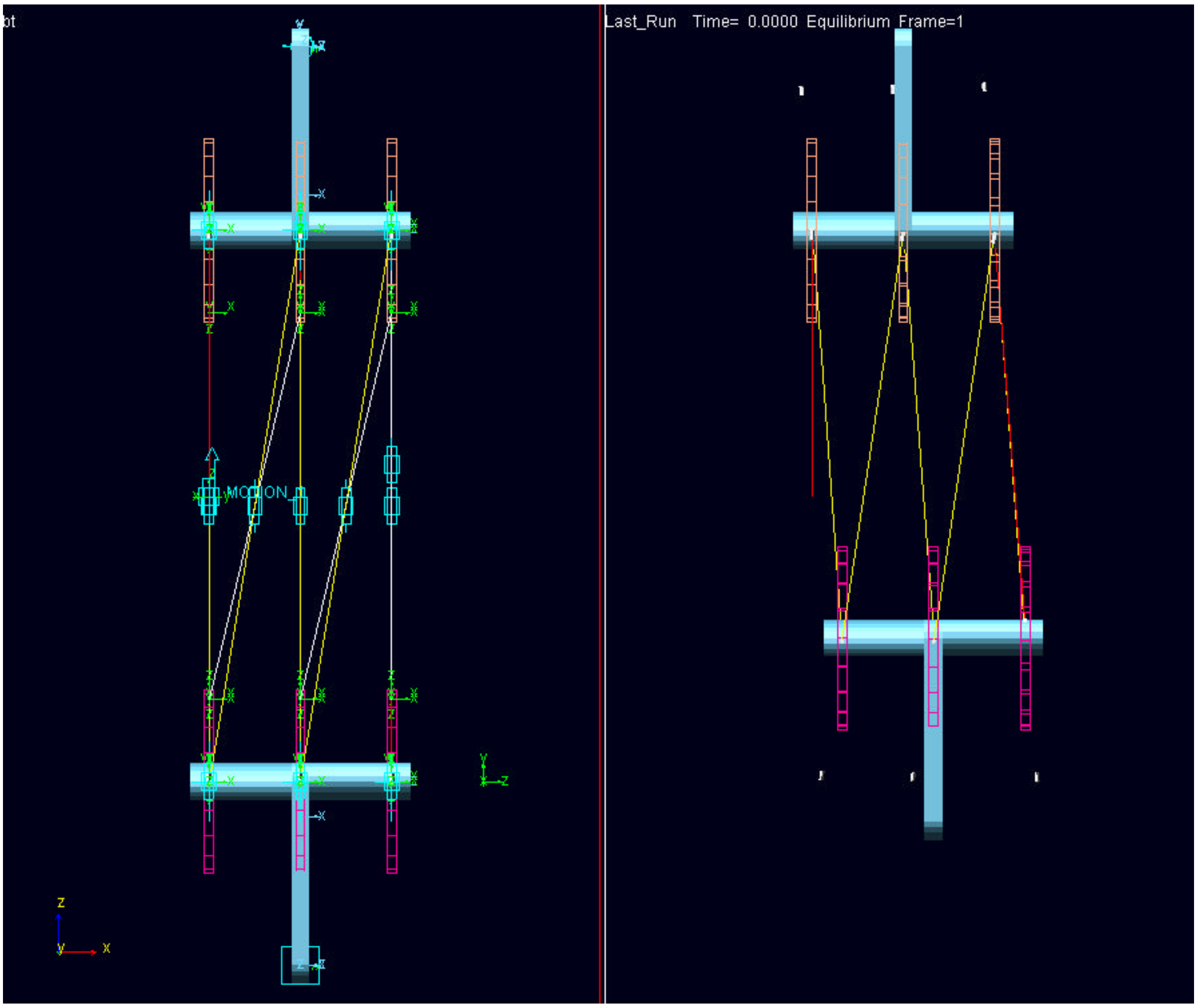
The rigid cable part itself, shown by the white cylinder, is connected to the turret with a translational joint. The motion of this translational joint is coupled to the rotation of the pulley body with a rack-and-pinion joint. (A coupler could also be used.)

By adding another dummy part between the tangency part and the turret, you can insert an extra translational joint which to allow the cable to move axially along the pulley. This is not desirable for a cable/pulley system, but is easily adaptable to a tape/capstan system as shown below with these translational joints highlighted.



Assembling a more complex model, such as a block-and-tackle or a tape drive, is simply done by adding multiple instances of this kind of pulley/cable subsystem. You do not have to exactly match up each input and output cable, but instead can take advantage of ADAMS' ability to assemble slightly misplaced parts as shown in this single block-and-tackle stage, shown both as built and as ADAMS assembles it.

In the 3-stage block-and-tackle shown here, you can see how nicely ADAMS does this by comparing the original configuration (as built) on the left, where even some of the joints do not line up, to the static equilibrium position shown to the right.



LEVEL 3 CABLE/PULLEY SYSTEMS

In this section, we will concentrate on modeling *extensible* cables in an efficient manner. The pulleys developed in the previous section can be used with the to-be-described new cable with just a bit of modification.

When considering problems where a large amount of cable will be injected into the dynamics, there are two basic approaches that can be considered:

1. Brute Force – The cable is made up of many sections of small masses (PARTs or POINT_MASSes) and spring-dampers, in a way very similar to Level 2 modeling. The part density in the model is determined by the kind of phenomena you need to capture. The inactive sections of cable have to be "stored" somewhere, for example around a drum, and a method has to be invented for allowing them to join the active simulation as the cable plays out.

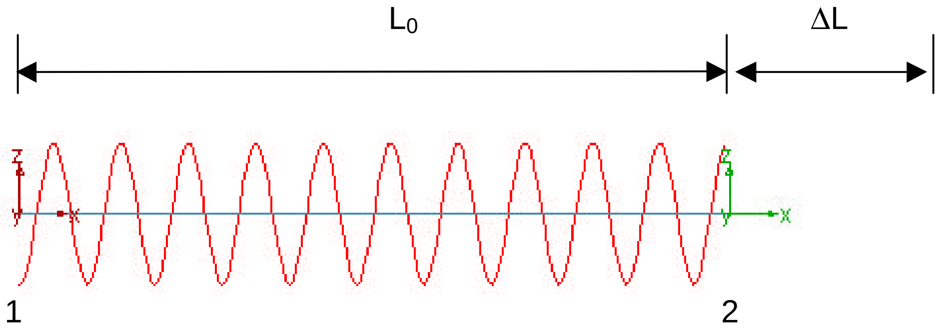
   This method has one advantage in that the cable sections are very simple to create and only standard ADAMS elements are used. However there is definitely a run-time problem, especially if a very large number of elements have to be in contact with storage drum or the like. This method will not be discussed further in this paper.

2. Variable-Mass / Variable-Length Cable Elements – An alternative to the brute force method is to use a fixed number of cable sections in the model, but somehow make them get “longer” as the cable plays out. A cable section includes both a spring-like compliant piece and a part-like inertial piece. So, this method would involve both changing the free length and stiffness of the compliant element, as well as the mass of the inertial element.

   ADAMS, unfortunately has neither of these two types of elements as base modeling entities. They, can, however, be created using a combination of SFORCEs for the compliant portion and PARTs (or POINT_MASSes) and VFORCEs for the inertial portion. This is described below.

VARIABLE-LENGTH “SPRINGS”

Imagine a section of cable that originally has length L_0 and stiffness EA/L_0 and then extends to have a new length ($L_0+\Delta L$):



The new stiffness for this section is now $EA/(L_0+\Delta L)$, while the dynamic elastic stretch of the section will be [DM(1,2)-($L_0+\Delta L$)]. This means we can write an SFORCE between each mass element pair that looks like:

SFORCE/0102, I=1, J=2, FUNCTION= -EA/(L_0+DL)*[DM(1,2)-(L_0+DL)]

Note that the ΔL term is not related to elastic deformation, but is determined by the amount of additional cable that is injected into the simulation. For example, if the cable had N sections and was playing straight out over a pulley of radius R that rotated through an angle α, then the ΔL would simply be $\Delta L = \alpha R/N$.

VARIABLE-MASS “PARTS”

Since ADAMS has no mechanism for dynamically changing the inertial properties of a PART, the variable mass approach uses the concept of d’Alembert forces to simulate these effects. That is, we use additional forces on existing fixed-mass parts to make them act as if they had varying mass. The general case for PARTs with moments of inertia is more involved, but for the problem of cable dynamics, we can ignore the effects of rotation and concentrate on translation. This implies that POINT_MASSes could be used, as well as PARTs, if desired.

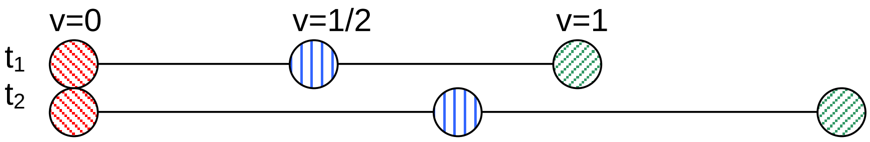
If the cable has a running mass of ρ per unit length, then the change in mass associated with the same ΔL used above is:

$$\Delta m = \rho\Delta L$$

To take advantage of the d'Alembert approach, we have to be sure to use total derivatives and to work in the global (inertial) reference frame. Starting from the relation F=d/dt(m*V), we have

$$\Delta F = \Delta m * dV/dt + V * d(\Delta m)/dt$$

The quantity $d(\Delta m)/dt$ should be directly available as $\rho*(d\Delta L/dt)$. Conceptually, one can imagine a case, using this kind of model, where a cable is rapidly extending from a pulley in one direction. In this case, the mass at the far end of the cable would be moving at the full speed of extension, whereas a mass near the pulley would be moving much more slowly. It is this second term in the above equation that accounts for this effect and prevents momentum from "piling up" at one end of the cable.

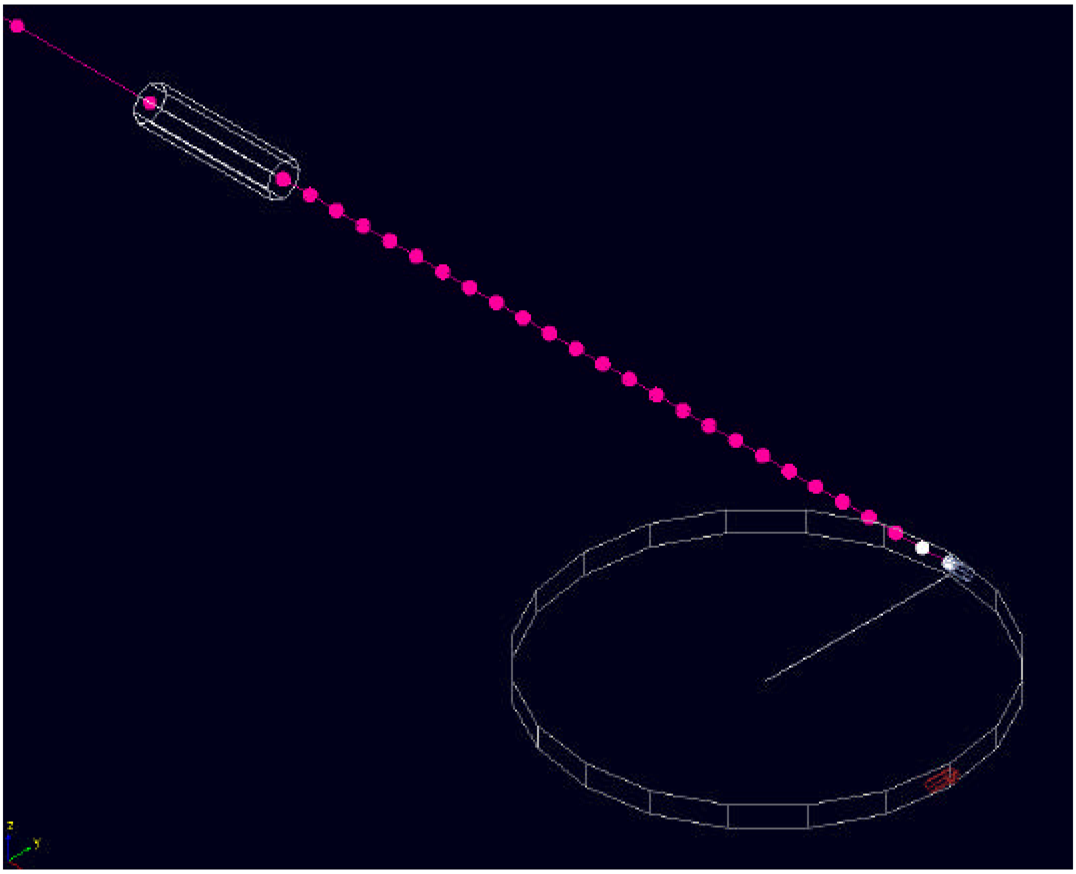


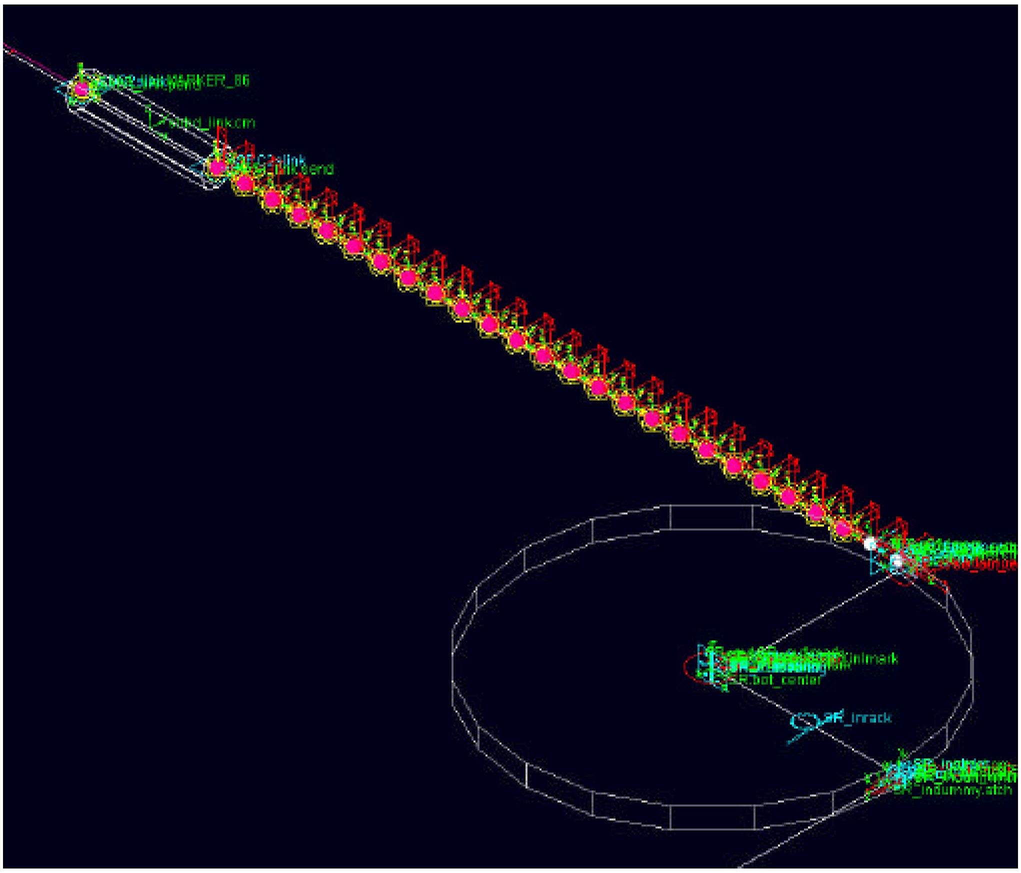
We must also be sure to not double count the acceleration due to gravity and also to account for the gravitation constant if the units system requires it. We can simplify the expressions somewhat by putting the Δm and $d(\Delta m)/dt$ quantities into data-element VARIABLEs. We then end up with an action-only "variable-mass" VFORCE (floating marker on the ground part) for each mass element in the cable, whose components are look like:

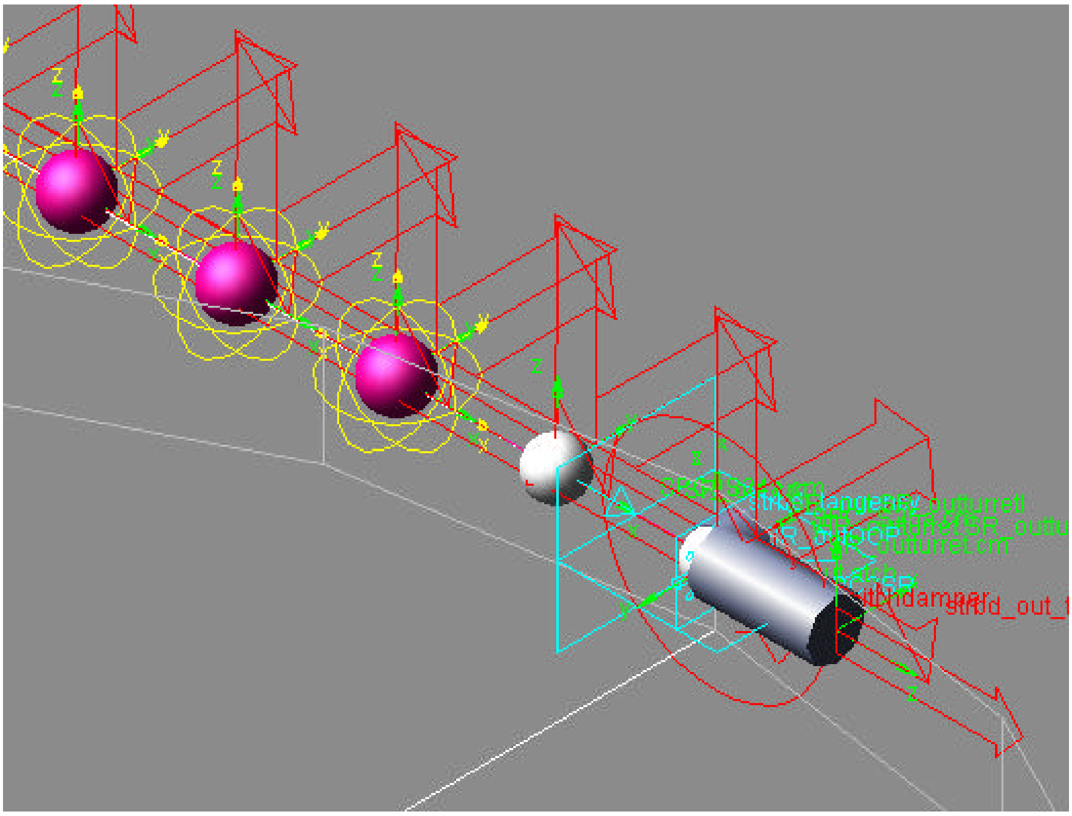
```
VFORCE/02, I_marker=(cm), J_part=(ground)
, FX= VARVAL(Dm) /GC * (ACCX(cm,0,0)-IGRAV)
,       + VARVAL(d(Dm)/dt) /GC * VX(cm,0,0) \
, FY= VARVAL(Dm) /GC * (ACCY(cm,0,0)-JGRAV)
,       + VARVAL(d(Dm)/dt) /GC * VY(cm,0,0) \
, FZ= VARVAL(Dm)/GC * (ACCZ(cm,0,0)-KGRAV)
,       + VARVAL(d(Dm)/dt) /GC * VZ(cm,0,0)
```

Note: There is a problem in ADAMS/Solver v12 with the use of sliding constraints (In-Line or In-Plane) and POINT_MASSes. If your model needs to use sliding constraints on the cable, as is often the case with pulleys, you must change the effected POINT_MASS elements to PARTs with an associated Orientation primitive joint connected to ground. These are shown as the white elements below in this view of one side of an aircraft carrier arrestment system. The second graphic shows the same system with all the icons for the variable elements displayed.

The third picture shows some of the details of how the cable is connected to the sheave. This involves various additional force elements and constraints, and a complete discussion is outside the scope of this paper. Please contact the author for more information.


z
y


MARKER_86
SR_inrack
SR_indummy.atch



VALIDATION RESULTS

The cable models have been validated against classical closed-form solutions for cable wave dynamics as given in an old U.S. Navy report (M-5933) by Friedrich Ringleb. This report gives results for both the axial wave dynamics (wave speed greater than 3000 m/s!) and for transverse wave dynamics (wave speed less than 100 m/s). Correlation for predicted loads due to the impact of the kink wave at the sheave were within 1% without requiring any parameter “tweaking”.

SUMMARY

1. A very useful pulley model has been developed that produces appropriate reaction forces at the mounting point, while allowing for dynamic cable wrap as well as slightly non-planar input and output.
2. A new combination element suitable for efficiently modeling extensible cables has been developed and validated. This element includes a variable-length spring SFORCE and a variable-mass PART or POINT_MASS using d’Alembert force functions in an associated VFORCE.
3. These elements can be used together to accurately model extensible cable dynamics and usefully expand the range of machine designs that ADAMS can simulate.

RINGLEB REPORT REFERENCES

1. “Summary of Information and Data on Cable Dynamics”, F.O. Ringleb, U.S. Naval Air Material Center Report M-5933, June 1955.

2. “Cable Dynamics”, F. O. Ringleb, Naval Air Engineering Facility Report NAEF-ENG-6169, December 1956.

LEVEL 2 MODELING REFERENCES

1. “Dynamic Analysis of an Automotive Timing Chain System”, S. Hwang & P. Pandolli, Ford; Y. Lin, S. McDonald & J. Weidman, Mechanical Dynamics, Inc., presented at the 1996 North American ADAMS Users Conference.

2. "Analysis of the Dynamic Effects of an Elastic Belt in a General Mechanical System", T. DePauw, Y. Lin, Y. Jiang, Mechanical Dynamics, Inc., presented at the 1997 North American ADAMS Users Conference.

3. “ADAMS/Engine - MDI´s New Development Tool for ValveTrain Dynamics, Timing Chain and Belt Drive”, C. Ortmann, Mechanical Dynamics, Inc., presented at the 1999 European ADAMS Users Conference.

4. “Development Of Dynamic Simulation Technique For Timing Chain System“, Tadasu Suzuki, Tsubakimoto Chain Co., presented at the 1999 Japanese ADAMS Users Conference.

5. “Simulation of Metal Pushing Type V Belt for CVT”, K. Kanokogi, Honda, presented at the 2000 European ADAMS Users Conference.