Computer Model for Dynamic Skyline Behaviour

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ABSTRACT

The development and experimental verification of a numerical model for the dynamic behavior of a cable logging system skyline is discussed. The model is intended to simulate the skyline behavior after a turn of logs breaks out of a "hang-up" on the ground. Output from the model may be used as a forcing function for a dynamic load on the tailspar or other component of the cable logging system.

The numerical model uses finite difference and Runge-Kutta techniques. Output from the model consists of time-histories of the fluctuations in skyline tensions. From this output the frequencies of the skyline vibrations may be determined. The model was verified by experimental data collected while operating a small cable logging system in Oregon State University's McDonald Research Forest.

Keywords: *cable logging system, cable dynamics, numerical modelling, skyline, tailspar, wave equation.*

INTRODUCTION

In the Pacific Northwest, skyline cable logging systems (Figure 1) are commonly used to harvest timber. Oftentimes, in rough terrain, tailspars are employed in the cable system to provide more lift for the skyline. In the past safety concerns over the selection of a tree as a tailspar were limited to the selection of sound trees; old-growth timber was nearly always large enough to provide excellent tailspars, and guidelines for the selection of tailspars were available [1]. Recently, however, the increased harvesting of second-growth timber has resulted in concerns over the performance and safety of tailspars. A necessary step in the effective prediction of tailspar performance is the determination of the loads, both static and dynamic, which are placed on the tailspar. An accurate computer model of skyline behaviour is one way to efficiently determine the loads placed on a tailspar.

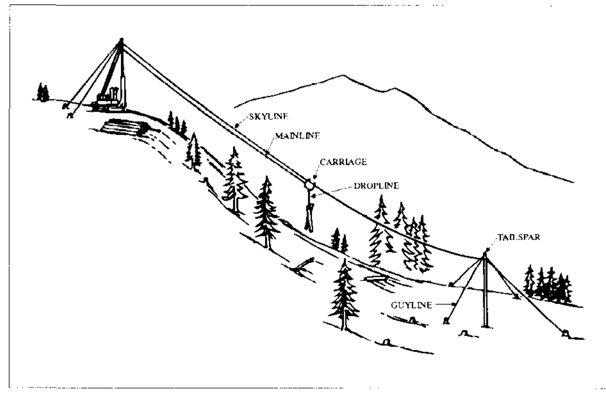

Figure 1. Typical logging system.

One circumstance that creates maximum tensions in the skyline and, therefore, maximum loads on a tailspar is the hang-up of a turn of logs on a ground obstacle during yarding and the subsequent release or "break-out" of the turn from the hang-up as the yarder operator reels in the mainline. This situation results in large quantities of stored elastic energy throughout the system. When the hang-up breaks loose, the release of this energy initiates dynamic free vibration behaviour in the skyline with resulting fluctuations in skyline tensions and, thus, tailspar loads. Through resonance [2,3] this dynamic loading could result in tailspar displacements and stresses greater than those induced by the maximum static hang-up load. This paper discusses a finite difference-based computer model developed to duplicate the dynamic skyline behaviour which results from this hang-up/break-out phenomena. This dynamic skyline model can be used to aid in determining the potential of a specific tailspar to resonate due to excitation from an oscillating skyline. Output from the model can also be used as input to a tailspar analysis program [4] to predict additional tailspar behaviour.

Development of the Numerical Model

In the numerical modelling of structural dynamics there are two options: finite elements or direct integration techniques. The dynamic behaviour of a cable logging system skyline is geometrically non-linear due to the large displacements which occur. Direct integration techniques, which avoid iterations and slow or non-convergence to a solution, are more suitable for this type of non-linear dynamics problem [5].

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The finite difference method is a direct integration technique well suited to the solution of nonlinear cable dynamics problems. The dynamic behaviour of a cable logging system skyline is similar to the classic problem of a vibrating string. In applied mathematics the partial differential equation that governs this type of behaviour is known as the "wave" equation, which is given here (in nonlinear form):

$$\frac{\partial^2 v_{x,t}}{\partial t^2} = \left(\frac{T\partial^2 v_{x,t}}{\rho \partial X^2}\right)\left(\frac{\cos\theta}{\left(1+\left(\partial v_{x,t}/\partial x\right)^2\right)^{1/2}}\right) \quad (1)$$

where $v_{x,t}$ is the displacement of the string, x the position along the string, t the time, T the tension in the string, ρ the linear mass density of the string and θ the angle of the cable at x.

The finite difference formulation of the wave equation is obtained by replacing the continuous differential terms in equation (1) with divided differences taken between discrete points, with respect to both time and distance along the string [6]. This type of solution is executed by first placing nodes along the string and incrementing the length of time over which the analysis is to occur. The distance between the nodes, Δx, and the size of time increment, Δt, are usually kept constant to maintain simplicity in the finite difference analysis. In a pictorial form this creates a grid, the value of the function $v_{x,t}$ at each grid point representing the displacement of the string at a specific position along the cable, x, for a specific time, t (Figure 2).

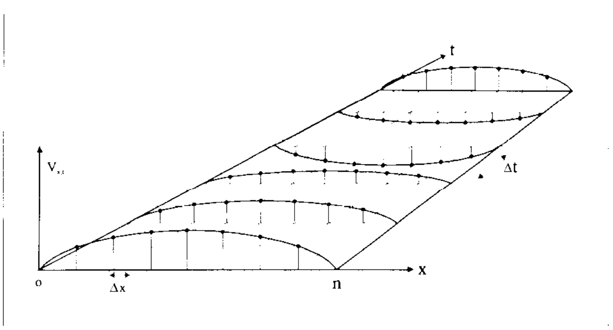

Figure 2. Finite difference visual.

The second order partial derivatives in the wave equation are approximated by second divided differences [6]. Utilizing these divided difference approximations for the partial derivatives, an algebraic approximation of the wave equation is formed:

$$\frac{v_{x_i,t_{j+1}} - 2v_{x_i,t_j} + v_{x_i,t_{j-1}}}{\Delta t^2} = \left(\frac{T}{\rho}\right)\left(\frac{v_{x_{i+1},t_j} - 2v_{x_i,t_j} + v_{x_{i-1},t_j}}{\Delta x^2}\right) \times \left(\frac{\cos\theta}{\left(1+\left(\frac{\left(\partial v_{x,t}\right)}{\partial x}\right)^2\right)^{1/2}}\right) \quad (2)$$

The i and j subscripts indicate the relative position along the cable and time step, respectively, for each function value, $v_{x,t}$. As the finite difference solution is being executed this equation contains a single unknown quantity, the displacement $v_{x_i,t_{j+1}}$.

To initiate the finite difference analysis the values of the displaced string are needed for the first two time steps, j=0 and j=1. The initial position of the cable, v_{x,t_0}, are typically known or easily calculated. The displacements of the skyline at the second time step, v_{x,t_1}, can be determined from the equation [7]:

$$v_{x_i,t_1} = v_{x_i,t_0} + \Delta t\left\{\frac{\partial v_{x_i,t_0}}{\partial t}\right\} \quad (3)$$

where the first partial derivative of v_{x,t_0} with respect to time is the initial velocity of the cable. A simplifying assumption, commonly used, is to set the initial velocity equal to zero. This results in v_{x,t_1} being equal to v_{x,t_0}. In other words, the displacement of the cable at the first time step, j=1, is set equal to the initial position of the cable at time j=0. This gives the values of the function, $v_{x,t}$, for the two time steps required to start the analysis. The results of the first pass of the finite difference solution would be the displacements at time j=2. The actual displacements of the cable at the first time step, j=1, are never determined. This double use of the initial conditions has little effect on the overall determination of the skyline displacements.

Once the analysis is started, equation (2) provides an algebraic equation at each node with a single unknown, $v_{x_i,t_{j+1}}$. The values of the function

$v_{x,t}$, the displacements of the string, and $\delta v_{x,t}/\delta x$, the slope of the string, are known for all nodes at times t=j-1 and t=j through solutions attained in previous time steps.

Stability of Finite Models

Equation (2) is the finite difference equation that comes directly from the divided difference approximation of the wave equation and is known as an explicit 5-point method; 5 values of the function $v_{x,t}$ are contained in the finite difference equation and a single unknown value, $v_{x_i,t_{j+1}}$, is determined from the equation. The stability of any finite difference approach is a function of the relationship between the nodal spacing, Δx, the size of time increment, Δt, the skyline tension, T, and the linear mass density of the skyline, ρ. If the following relationship (the Courant-Friedrichs-Lewy condition [8]) is true for the given values of these variables, then stability of the finite difference solution is guaranteed:

$$\frac{(\Delta t)^2 T}{(\Delta x)^2 \rho} \leq 1 \tag{4}$$

If this relationship is not true, then the finite difference solution is unstable in that it attempts to determine values of the cable displacement, $v_{x,t}$, which are beyond its influence.

Given tensions that can occur in cable logging system skylines, from a few thousand to tens of thousands of pounds, it is often quite difficult to use the explicit 5 point method and meet the conditions of equation (4) without using very large values of Δx, tens of feet on a skyline, or taking extremely small time steps, thousandths of a second in size. Large distances between nodes on the cable would reduce the accuracy of the solution, while small time steps would require lengthy computational run times.

One solution to this predicament is to utilize a finite difference scheme which does not experience stability problems. Several such approaches are known [9,10], the one selected for this skyline model is an implicit, three unknowns in a single algebraic equation, finite difference method containing 9 values of the function $v_{x,t}$. This approach is a weighted average of 3 different 5 point schemes [11], including the 5 point explicit scheme discussed previously. Using a shorthand notation for the basic divided difference numerator, as an example the numerator of the second partial of v_{x_i,t_j} with respect to x:

$$\delta_x^2 v_{x_i,t_j} = v_{x_{i-1},t_j} - 2v_{x_i,t_j} + v_{x_{i+1},t_j} \tag{5}$$

we can express the algebraic equation which results from this 9 point finite difference technique:

$$\delta_t^2 v_{x_i,t_j} = \left(\frac{T(\Delta t)^2}{\rho(\Delta x)^2}\right) \times \left(\frac{\delta_x^2 v_{x_i,t_{j-1}} + 2\delta_x^2 v_{x_i,t_j} + \delta_x^2 v_{x_i,t_{j+1}}}{4}\right) \times \left(\frac{\cos\theta}{\left(1+\left(\frac{\delta v(x,t)}{\delta x}\right)^2\right)^{1/2}}\right) \tag{6}$$

As mentioned previously, the implicit nature of this algebraic equation results in three unknowns for a single equation. However, if the finite difference equations are solved simultaneously for all the nodes, x_1 to x_{n-1}, at the j+1 time step, the result would be n-1 equations with n-1 unknowns, the cable displacements at time t_{j+1}. The known endpoint displacements, v_{x_o,t_j} and v_{x_n,t_j}, which are typically zero, would be used in equations developed near the endpoints. The result is a tridiagonal system of n-1 equations which can be solved using any number of existing methods. In this approach all the values of skyline displacements, $v_{x,t_{j+1}}$, are determined simultaneously, and then the time is increased by one increment, Δt, and the solution repeated for the duration of analysis, the length of which is specified by the program user.

Skyline Model

The objective of this skyline model is to determine the fluctuations in tension and free vibration frequencies of a skyline that hangs up and subsequently "breaks-out." These tensions and frequencies, which may be extracted from a finite difference time history analysis, are intended for use in evaluating tailspar performance and adequacy.

The major physical element of a cable logging skyline which separates it from the simple vibrating string problem is the large point mass on the skyline created by the carriage and turn of logs. This point mass essentially breaks the skyline into two segments. The computer model developed treats the skyline as two separate "string" segments with a shared, moving (in the transverse direction) boundary condition, the carriage. This allows the use of the finite difference approximation on each of the two cable segments, once the position of the moving boundary (carriage) is ascertained at each time step. The determination of the carriage position is based on a fourth order Runge-Kutta solution [12] of the differential equation derived from force equilibrium in the direction transverse to the chord of the cable. The derivation of this differential equation was first documented by Tychonoff and Samarski [13]. In the original work the effect of gravity was neglected; however, for this application inclusion of the gravitational effects is essential, resulting in the following force equilibrium equation:

$$m\left(\frac{\delta^2 v_{c,t}}{\delta t^2}\right) = T_L \sin\alpha + T_R \sin\beta + mg \qquad (7)$$

where m is the mass of the carriage and an appropriate portion of the turn of logs, g the acceleration of gravity, $v_{c,t}$ the displaced position of the carriage, T_L the tension in the skyline to the left of the carriage and T_R the tension in the skyline to the right of the carriage. The trigonometric functions are used to calculate the component of the skyline tensions transverse to the cable chord and are based on the angles of the tangents to the skyline directly on either side of the carriage (see Figure 3). The terms on the left side of the equation are due to the weight of the carriage and turn of logs plus the inertial force created by the motion of the skyline. Through the Runge-Kutta solution of equation (7), the displaced position of the carriage at the next time step, $v_{c,t_{j+1}}$, is determined based on the known position of the carriage at the current time step, v_{c,t_j}.

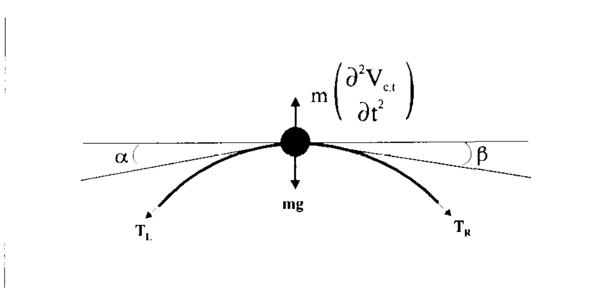

Figure 3. Force equilibrium.

The fluctuations in skyline tension are a function of the carriage displacement. In a simplified string problem the tension of the string is considered to be a constant. However, this is not the case with a cable logging system skyline which experiences extreme variations in tension during dynamic behaviour. The point mass consisting of the carriage and turn of logs is very large compared to the mass of the skyline. This results in skyline behaviour which is similar to a single lumped mass dynamic system. In a single lumped mass system the only active dynamic mode is the first, or fundamental, mode. Hence, the fundamental mode should be the dominant mode — the mode primarily responsible for variations in the tension of the skyline. The first mode shape is a function of the carriage position; by determining the position of the carriage, as outlined previously, and neglecting the other modes which may occur within the cable segments on either side of the carriage, the variations in skyline tension can be determined by the change in distance between the carriage and the supports. As the distance between the carriage and the supports increases beyond the initial conditions, the skyline elongates and the tension in the skyline increases. Conversely, as the distance between the carriage and the supports decreases to less than the initial conditions, the skyline relaxes and the tension decreases. The basic relationship between changes in tension and elongation of an axially loaded element is [14]:

$$\Delta T = \frac{\Delta L}{L_0} \times A \times E \qquad (8)$$

where ΔT is the change in element tension, ΔL the change in element length, L_0 the original length of the element, A the cross-sectional area and E the modulus of elasticity. Again, utilizing this relationship and the position of the carriage relative to the supports, the variations of the skyline tension during dynamic behaviour may be determined.

This first-generation computer model contains several simplifications of the complicated skyline logging system. First, the skyline supports (tailspar and yarder) though flexible to some degree were considered as rigid supports. Second, damping and motion of the carriage along the skyline, which influences the damping, are not included in the computer model. However, some numerical damping does occur in the Runge-Kutta solution for the position of the carriage. Third, no elevation change between the tailspar and yarder is considered, a simplification that maintains a one-dimensionality to the skyline displacements and eliminates the need to express the skyline displacements in vector form. With this simplification the model may be applied to skyline systems that have a moderate change in grade between the tailspar and yarder (10% or less) without inducing large error into the analysis.

Model Input/Output

The required input, listed below, to execute the model is such that it specifies the criteria for the finite difference analysis and indicates the mechanical properties of the skyline and the conditions of the cable logging system at the time of the hang-up:

- skyline chord distance from tailspar to yarder;
- length of skyline from tailspar to tailhold;
- diameter of skyline;
- estimated initial tension in skyline (prior to hang-up);
- weight per foot of skyline;
- spacing between nodes along the skyline;
- weight of the carriage;
- estimated weight of the turn of logs;
- size of time steps;
- length of time history analysis;
- distance from tailspar to carriage at hang-up;
- estimated amount of carriage displacement due to hang-up.

The output, in the form of time histories, is the variation in the skyline tension and the displacements of the skyline and carriage. The frequency of the skyline oscillations can be determined from the skyline tension changes. The variations in skyline tension may be used as input, a forcing function, for the dynamic analysis of the tailspar or other components of a cable logging system.

Comparing the frequencies of the skyline oscillations with the natural frequencies of other system components (e.g., tailspar) will reveal the potential for resonance [2,3] within the cable logging system. If the natural frequency of the tailspar matches the frequency of the skyline vibrations resonance may take place, resulting in larger displacements and stresses than would normally occur in the tailspar. Determining the potential for resonance is critical in the prediction of tailspar behaviour in the field. An indication that resonance might occur for a selected tailspar could help to avoid a tailspar failure.

Verification of the Model

In order to confirm the effectiveness of the computer model, a small cable logging system was erected in Oregon State University's McDonald Research Forest. The chord length of the skyline (15.875 mm [5/8 inch] diameter wire rope) in this system was 100 m [330 feet] with a vertical rise of 7.62 m [25 feet], for an incline of 7.58%.

The field tests were designed to imitate the hang-up and break-out phenomenon for a turn of logs. Calibrated load cells were placed in the skyline and dropline (see Figure 1) to obtain the necessary values of cable tensions required to verify the model. An IBM personal computer with a data acquisition card and software was used to collect the data from these tests, floppy disks were used to store the data. A sampling rate of 0.02 seconds was used for the data acquisition. The data gathered from the load cells, in terms of volts, was later converted to tension, with units of pounds or kilonewtons, by using a spreadsheet. The conversion factor used was obtained through the calibration of the load cells.

The simulation was accomplished by bringing the skyline up to a reasonable tension, tying the turn of logs to a stump with a nylon rope and then engaging the yarder to reel in the carriage/log load until the rope broke. Five field tests, executed at different distances along the corridor depending on the availability of useable stumps to tie the rope to, were used for comparison with the computer model.

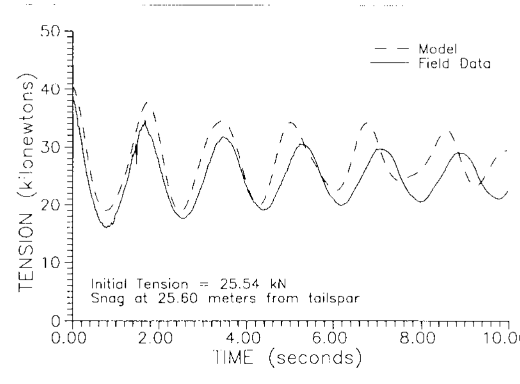

Figure 4. Skyline tension, hang-up test #1.

Table 1. Comparison of field data and computer model.

Test No.	Initial Carriage to Tailspar Distance	Initial Skyline Tension	Maximum Skyline Tension			Maximum Envelope Skyline Tension (2 x Max. Amplitude)			Maximum Amplitude Skyline Tension		
			Field	Model	Model %Error	Field	Model	Model %Error	Field	Model	Model %Error
1	25.60	25.54	39.05	40.57	3.9	22.74	21.55	-5.2	0.574	0.584	1.7
2	36.12	28.04	42.35	41.71	-1.5	22.04	20.90	-5.2	0.574	0.620	8.2
3	46.94	25.04	35.25	36.66	4.0	14.51	18.32	26.2	0.562	0.610	8.5
4	60.05	26.28	34.25	36.09	5.4	13.51	16.27	20.5	0.574	0.526	-8.3
5	68.28	23.91	29.17	30.50	4.5	10.36	10.92	5.4	0.598	0.620	3.9

Tensions measured in kilonewtons. Distances measured in metres

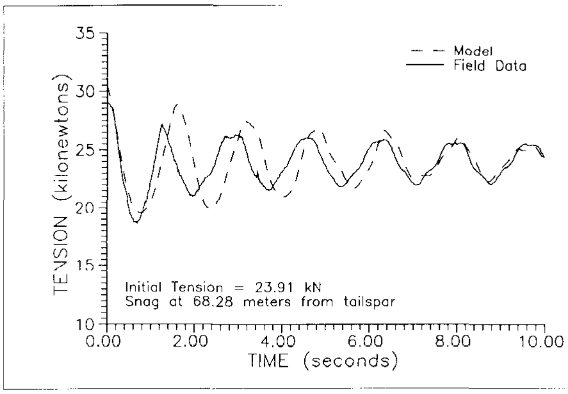

Figure 5. Skyline tension, hang-up test #5.

Variations in the skyline tensions, obtained through the load cell placed in the skyline, were used to verify the computer model. Figures 4 and 5 are two examples of the variations in skyline tensions for field tests overlayed on output from the computer model. For this computer simulation a Δx of 0.1524 m [0.5 feet] and a Δt of 0.05 seconds were used for the finite difference approximations. Time histories developed by the computer simulation for comparison with the field tests were 10 seconds in length (200 time steps).

DISCUSSION

A comparison of the field test results and output from the computer model is contained in Table 1. The errors in the model predictions of maximum skyline tensions and skyline frequencies for the five tests are all under 10%. The maximum error for the skyline tension is 5.4% and for the skyline frequency 8.5%. The largest error for the computer model came in determining the maximum envelope (2 x maximum amplitude) of the damped sinusoidal skyline tension curve. In this case the computer model had an error of over 20% for two of the tests, with the error for the remaining three tests at around 5%. The two model predictions for which there were large errors, however, were on the conservative side; the model predicted larger amplitudes of change in the skyline tension than actually occurred.

Overall, the model has done nicely in predicting the dynamic behaviour of the skyline within the small cable logging system set up for the purpose of verifying the model. Given the simplifications of the physical system that are contained in the model and the difficulty in controlling the equipment used in the field tests (a diesel yarder, 330 feet of skyline, a carriage, 1000 pound log, etc.) which made it hard to determine precisely the initial conditions of the cable system, model error which is consistently less than 10% is highly acceptable.

The objectives of developing this model were to provide information for the analysis of tailspars. The variations in skyline tension can be used as input, a forcing function, for the dynamic analysis of the tailspar or other components of a cable logging system as well. Comparing frequencies of the skyline oscillations with the natural frequencies of the tailspar will reveal the potential for resonance [2,3]. If the natural frequency of the tailspar matches the frequency of the skyline vibrations resonance may take place, resulting in larger displacements and stresses within the cable logging system than would normally occur. Though the tests used to verify the skyline model indicated no resonance in the tailspar for this particular skyline logging system, this was not known before the tests and may not be the case for other larger skyline logging systems. This dynamic skyline model can be used prior to the erection of a skyline logging system to aid in determining the potential for resonance in a tailspar. An indication that resonance could occur for a selected tailspar would be reason for selecting an alternate spar in order to avoid a tailspar failure.

CONCLUSION

A simple, first generation numerical model for the dynamic behaviour of a skyline has been developed. Output from this model compares quite well to the results of field verification tests. Excellent estimates for maximum skyline tension fluctuations and frequencies were obtained through the model and will serve well in helping to determine the likelihood of tailspar resonance and as input to a tailspar analysis program.

Future work on this model should include modifications to account for cable logging systems set up on steep slopes or extremely long span systems that may or may not contain intermediate supports.

REFERENCES

[1] USDA Forest Service. 1978. Logging Systems Guide. Division of Timber Management, Region 10, Series R10-21, 43.55-7, Juneau, Alaska.

[2] Craig, Roy R., Jr. 1981. Structural dynamics, an introduction to computer methods. John Wiley and Sons, New York.

[3] Biggs, John M. 1964. Introduction to structural dynamics. McGraw-Hill, New York.

[4] Ammeson, James E., Marvin R. Pyles and Harold I. Laursen. 1988. Three-dimensional analysis of guyed logging spars. Computers and Structures, 29(6): 1095-1099.

[5] Cook, Robert D., David S. Malkus and Michael E. Plesha. 1989. Concepts and applications of finite element analysis. 3rd ed. John Wiley and Sons, New York.

[6] Curtis, Gerald F. and Patrick O. Wheatley. 1984. Applied numerical methods. 3rd ed. Addison-Wesley, Menlo Park, California.

[7] Isaacson, Eugene and Herbert B. Keller. 1966. Analysis of numerical methods. John Wiley and Sons, New York.

[8] Courant, R., K. Friedrichs, H. Lewy. 1928. Uber die partiellen differenzengleichungen de mathematischen Physik. Mathematische Annalen, 100: 32-74.

[9] Crank, J. and P. Nicolson. 1947. A practical method for numerical evaluation of solutions of partial differential equations of the heat conduction type. Procedures of the Cambridge Philosophical Society, 43: 50-67.

[10] Smith, Gordon D. 1978. Numerical solutions of partial differential equations. 2nd ed. Oxford University Press.

[11] Womack, Kevin C. 1989. The dynamic behavior of a cable logging skyline and its effect on the tailspar. Doctoral dissertation, Department of Civil Engineering, Oregon State University, Corvallis, Oregon.

[12] Lapidius, Leon and J. H. Seinfeld. 1971. Numerical solution of ordinary differential equations. Academic Press, New York.

[13] Tychonoff, A.N. and A.A. Samarski. 1959. Differentialgleichungen der mathematischen physik. Veb Deutscher Verlag Der Wissenschaften, Berlin.

[14] Timoshenko, Stephen P. 1972. Mechanics of materials. Brooks/Cole, Monterey, Cal.