

Dynamic Characteristics of a Small Skyline Logging System with a Guyed Tailspar

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ABSTRACT

A series of dynamic loading tests were conducted on a small skyline logging system (15.8 mm [5/8 inch] skyline) operating in a second-growth Douglas fir stand. The tests included free vibration tests and logging tests with turns weighing from 1.5 to 9 kN [340 to 2050 lbs]. Natural frequency and damping were evaluated from free vibration tests, and the free vibration portion of logging tests. Dynamic load magnitude was evaluated for logging tests with natural and artificial breakouts of turns with a range in turn weights, and for a series of logging tests with the same turn. The natural frequencies of the guylines were in good agreement with simple cable theory. However, the presence of the carriage on the skyline resulted in measured natural frequencies significantly lower than simple cable theory would predict. Damping of the tailspar system and the skyline averaged about 10% of critical damping, but was highly variable from test to test. Dynamic load magnitude, whether expressed as the load peak produced by turn break-out, or the maximum cyclic load, was highly variable, with coefficients of variation ranging from 31 to 79%.

Even a series of logging tests with the same two-log turn produced maximum cyclic loads with a coefficient of variation of nearly 40%.

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INTRODUCTION

Cable logging is an important timber harvesting method in the Pacific Northwest region of North America [19]. The decreasing size of merchantable timber in the region [20] means that loggers will have to handle more pieces for the same timber volume than with larger timber. This increase in material handling has fostered an increased interest in fully but safely loading cable logging systems during production operations. Safe loading is linked to the static payloads that are carried by the cable system, and also the magnitude of the dynamic loads that occur during the yarding cycle.

Determination of the safe loading of a cable logging system must consider the entire structural system (Figure 1). The manufactured components — wire rope, carriages, blocks and shackles, and the yarding tower — have reasonably well-defined properties, but the arrangement of the components and the manner in which the yarder is operated can strongly influence safe loading. The natural components — stump anchors, and spar-trees — have less well defined properties [14, 15], and can also influence the safe loading.

Several authors have studied the behaviour of the various components of cable logging systems subjected to static loadings [1, 4, 5, 13], but far less study has been devoted to dynamic loadings. Numerical models created to simulate the dynamic behaviour of a skyline logging system have been

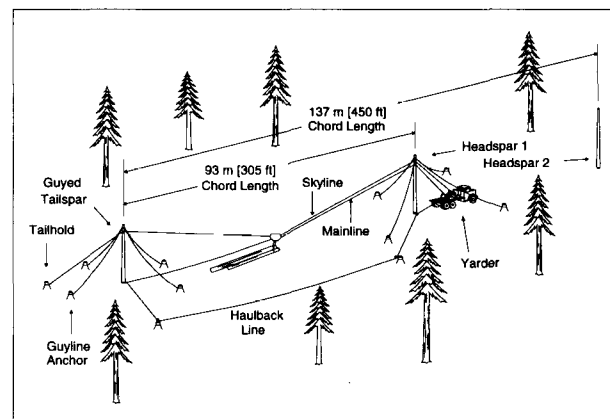


Figure 1. The skyline logging system configuration tested.

reported [3, 21, 22, 23], but they require detailed information on the dynamic characteristics of cable systems for proper calibration and verification. This paper reports the results of dynamic load tests on the elements of a short span skyline logging system with a tailspar, operating in a second-growth stand. The measured natural frequencies of the skyline, guylines, and tailspar, plus damping and load characteristics, are discussed.

DYNAMIC CHARACTERISTICS

Structural dynamics is complex, and it is the subject of many texts and much literature. It is not possible to fully develop the subject of structural dynamics here, but a few introductory comments will serve to explain the importance of various dynamic characteristics.

Natural Frequency

The natural frequencies of a system, or system component, are the frequencies at which the system will inherently oscillate if left to oscillate freely and at which resonance will occur if the system is excited at any one or more of those frequencies. Resonance can result in dynamic load magnification in which the peak response of the structure is magnified above the static response to the same magnitude load. Each natural frequency corresponds to a "mode shape" which for simple structures is the deflected shape of the structure when excited at the corresponding frequency. The first natural frequency normally dominates the response of a structure, and usually only the first few natural frequencies need to be considered to adequately describe dynamic response [6, 17]. Resonance and dynamic load magnification can be avoided by modifying a structure to insure that the natural period(s) of the structure do not coincide with the predominant period of the dynamic forcing load. If resonance cannot be avoided, then dynamic load magnification factors to account for it must be used in the design process.

Damping

Damping within a structural system results from energy loss into the supports and surrounding medium, internal work within the structural materials, and friction in connections [9]. In a system that is vibrating freely, damping causes the magnitude of the oscillations to decrease as energy is dissipated. Damping limits the response of a structure to dynamic loads, even if a structure is excited at one of its

natural frequencies. The amount of damping within a system can be determined only through experimentation.

Dynamic Load Magnitude

The simplest way to include dynamic loads in the analysis of a cable logging system is to include a dynamic load factor in the static analysis of the system. This has the advantage of being simple, but the disadvantage that the dynamic properties of the system which may produce load magnification are not taken into account. If dynamic analysis indicates that load magnification will not occur, then adequate treatment of dynamic loads can be achieved by including a dynamic load factor. If load magnification is likely, then full dynamic analysis with an appropriate dynamic load will be required. Either way, experimental data on dynamic loads are necessary to provide input to the analysis procedure.

TEST METHODS

Field Site

The test site was located in a 50-year-old second-growth mixed Douglas fir and hardwood stand located in Oregon State University's McDonald Forest. The main forest canopy consisted of Douglas-fir that were 30 to 50 cm [12 to 20 inches] DBH (diameter at 1.37 m [4.5 feet] above ground) and approximately 29 m [95 feet] tall. The hardwoods were generally less than 30 cm [12 inches] DBH and 18 m [60 feet] tall. The stand was typical of many stands being commercially thinned or clear-cut harvested.

Skyline System

The rigging and equipment was representative of a small skyline logging system (Figure 1); the skyline was 15.8 mm [5/8 inch] diameter wire rope; the mainline and tailspar guylines were 11.1 mm [7/16 inch] wire rope; the haulback was 7.9 mm [5/16 inch] wire rope. The carriage rides a sheave on the skyline and is moved up and down the corridor with the mainline and haulback. Power was provided by a three drum Skagit BU-40 yarder with a 82 kW [110 horsepower] diesel engine. The maximum tension generated in the skyline during yarding was approximately 80 kN [18,000 lbs]; static skyline pretensions before beginning a test ranged from about 4.5 to 45 kN [1,000 to 10,000 pounds]. The mainline operating speed varied from 18 to 58 m/min [60 to 190 feet per minute] during inhaul. The yarder

was not equipped with an integral tower, so two standing trees were topped and rigged as headspar to give skyline spans of 93 m [305 feet] and 137 m [450 feet].

The carriage, made by Christy Manufacturing, weighed approximately 0.78 kN [175 lbs]. Although designed for a gravity outhaul, the moderate slope of the test corridor (15 %) required a haulback line to pull the carriage out. The carriage was a locking type that ran onto a stop clamped to the skyline. The mainline and attached chokers release from the carriage when the carriage locks onto the stop. Conversely, the carriage releases from the stop when the chokers are pulled back into the carriage with the mainline.

A 50-year-old Douglas fir tree that measured 34.3 cm [13.5 inches] DBH was topped at 10.67 m [35 feet] and rigged for a tailspar as shown in Figure 2. The spar was guyed to stumps with four lines (11.1 mm [7/16 inch] diameter) that were attached as shown in Figures 2a and 2b. The turnbuckle illustrated in Figure 2a was used to tighten the guylines to specified tensions prior to skyline loading.

Instrumentation

Instrumentation of the cable system centred around the tailspar. Spar displacement and base rotation were measured in orthogonal planes to define the movement of the spar in a horizontal plane. Horizontal deflection at the top and mid-height of the spar was measured with variable potentiometer position transducers linked to the test trees by 1.6 mm [1/16 inch] diameter aircraft cables tensioned with 17.8 N [4 lb] lead weights (Figure 2c). Base rotation was measured using linear variable differential transformers (LVDT's) mounted on rigid frames attached to the base of the tailspar (Figure 2d).

Line tensions were measured using electronic load cells in the four guylines, skyline, and at the block hung in the tailspar (Figure 2). The load cells were direct tension devices which utilized a full wheatstone bridge resistive strain gauge circuit to provide temperature compensation and maximum electrical signal-to-load response. For a number of the tests, a load cell was rigged to measure the mainline tension or an artificial hang-up designed to create a dynamic load input to the system. Instrument precision is summarized in Table 1.

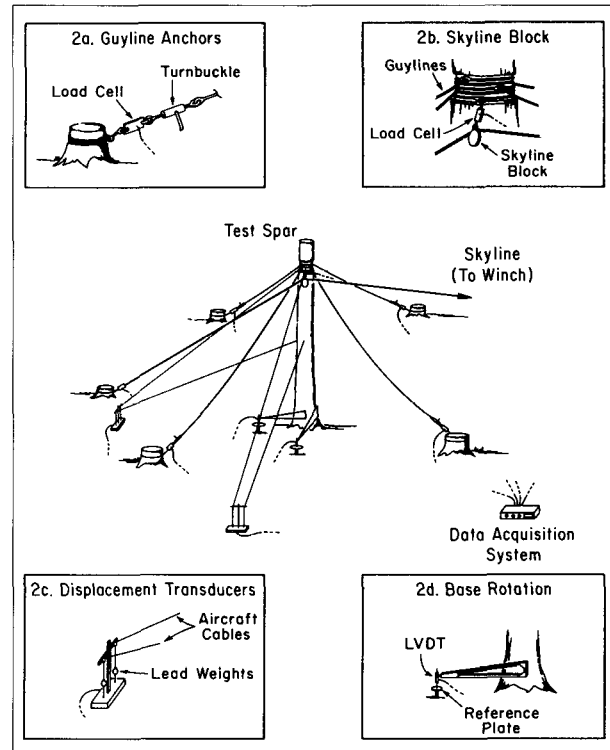


Figure 2. Tailspar rigging and instrumentation.

Test Description

Data were acquired by using a computer controlled system that was capable of scanning 12 channels approximately 10 times per second, limiting frequency measurements to less than 5 Hz (the Nyquist frequency [2]). Previous testing suggests that the frequency response of the skyline ranges up to 2 Hz [21]. Fewer channels were monitored during guyline plucking tests, giving a scanning rate of 30 times per second which allowed frequencies as high as 15 Hz to be detected.

Three series of tests, described below, were conducted to establish the dynamic behaviour of the skyline system. Although numerous variables may affect the response of the skyline and guyed spar systems, the cost and time required for extensive rigging changes limited testing to a single skyline corridor and tailtree. The parameters varied were skyline length (93 m and 137 m corridors [305 feet and 450 feet respectively]), static skyline tension (4.5 to 45 kN [1,000 to 10,000 lbs]), and turn size (1.51 to 9.12 kN [340 to 2,050 lbs]).

Table 1. Test instrumentation.

Measurement function	Instrument	Range	Maximum error
Spar Displacement	position transducer	±25.4 cm	25 mm
Spar base rotation	LVDT ¹	±0.6 deg.	0.003 deg.
Guyline tension	load cell	0-20 kN	0.1 kN
Skyline tension	load cell	0-90 kN	0.45 kN
Spar loading	load cell	0-50 kN	0.27 kN
Mainline and Hang-up loads	load cell	0-20 kN	0.1 kN

¹ Maximum error of 0.13 mm through a range of ±2.5 cm.

Natural Frequency and Damping

The spar, guylines, and skyline were plucked to determine the natural frequencies and damping characteristics. Guylines were plucked by hand at the midpoint of the cable segment and released to vibrate freely in a vertical plane. The skyline was plucked by pulling the locked carriage down to a stump with the mainline and releasing it to vibrate freely in a vertical plane. The spar was plucked by pulling the spar horizontally with a hand winch attached to the spar top and releasing the winch line.

Corridor Yarding

The corridor yarding tests consisted of yarding a test load of logs up the skyline corridor with the leading end of the logs suspended from the carriage. As the logs were yarded over the uneven ground of the skyline corridor, a cyclic loading resulted. All the structural components of the system experienced cyclic loads as a result. The mainline most directly experienced the cyclic force since it is connected directly to the logs through the carriage. The skyline experienced a cyclic tension fluctuation associated with increases and decreases in vertical deflection of the skyline from the chord line. Changes in skyline tension produced a cyclic load on the spars. In one series of tests, a 9.12 kN [2,050 lbs] load consisting of two 10.4 m [34 foot] logs was used repeatedly (the logs were yarded back down the skyline corridor using the haulback). For some of these tests, an artificial hang-up was rigged by tying the logs to a stump with a fibre rope (breakout load between 10.7 to 13.3 kN [2,400 to 3,000 lbs]). A load cell was placed between the stump and rope to measure the impulse load that resulted when the fibre rope became taut and then broke as the logs were yarded along the corridor.

Full Cycle Yarding

Lastly, measurements were taken during actual logging operations. Douglas fir logs and whole-tree hardwood logs were yarded to the landing from various locations down and to the side of the skyline corridor. Again, artificial hang ups were rigged so the response to simulated breakout loads could be measured. Natural hang-ups were also experienced when logs caught on an obstruction such as a stump or standing tree. For several of the logging tests, a load cell was placed between the logs and the mainline.

Data Analysis Methods

Forty-four multiple phase dynamic load tests of up to 2 minutes and 40 seconds duration were conducted during the study. The longest tests resulted in data files containing up to 25,000 floating point instrument readings with respect to time. Much of the information in the data files is unique to the individual tests, and would be of little value in a general understanding of cable logging system dynamics. We extracted the more general components: dynamic load frequency content, displacement frequency content, system damping, and dynamic load magnitude.

Analysis and interpretation of skyline tensions was relatively straightforward. The tailspar movements and guyline tensions were more complicated. The instrumentation system produced four records of guyline tension (one for each guyline), and four records of spar movement (movement in two directions at the top and the mid-height of the spar). Because of the geometry of the tailspar and guylines, and the tension in the guylines imposed by the static skyline pre-load prior to the dynamic portions of the

tests, the two “rear” guylines carried all of the load that resulted from the dynamic skyline tension fluctuations, and one of the two rear guylines carried the majority of the load. The other two guylines were slack, and had a minimal effect on the dynamic behaviour of the system even though there was considerable spar-top movement in the plane of those guylines during some dynamic loadings. For simplification, system behaviour is described using the greatest loaded guyline tension and spar top displacement in the direction of the skyline corridor.

Frequency Content

The natural frequency of a complex structure like a cable logging system often must be obtained by observation of dynamic response of the structure. In some cases, an analytical model of the structure may be useful in evaluating the natural frequency. Of interest in this phase of the study was, first, the measured natural frequencies of the components of a cable logging system, and second, the correspondence between simple analytical models for estimating the natural frequency of the components of a cable logging system, and our field response measurements. Estimates of the natural frequency of a guyed spar which is a complex structure require complex analysis that is beyond the scope of this paper. However, a simple model for natural frequency exists for cables because cable segments are fairly simple structural components.

A cable segment can vibrate in a longitudinal mode (extension), an out-of-plane mode (swinging), or in an in-plane mode (transverse). The longitudinal mode is excited at relatively high frequencies and should be of little consequence for a cable logging system [21]. The out-of-plane mode is most easily excited in cables with a lot of sag. This mode may be observable in relatively slack unloaded skylines, but is unlikely to occur during yarding even if there is significant transverse deflection. The in-plane mode is the primary mode expected to appear in most tailspar guylines which are usually relatively taut, and may be the mode observed in taut skylines.

The natural frequencies of a taut cable vibrating in-plane (transverse motion) are given by [16]:

$$f_n = \frac{n}{2L} \sqrt{\frac{T}{m}} \quad (1)$$

where: f_n = the n th natural amplitude frequency, Hz
 L = length of cable segment, m
 T = initial cable tension, N
 m = mass of line per unit length, kg/m

The natural amplitude frequency is the inverse of the time required for the cable to complete a full cycle in transverse movement. The field instrumentation did not record transverse movement, but rather cable tension, therefore, some interpretation of the frequencies obtained from equation (1) is necessary for theory to be compared to field measurements.

If the cable in the field is taut, then the amplitude extremes, of which there are two in each amplitude cycle, should be expected to produce similar high-tension extremes. The least amplitude values which occur when the cable passes through a straight line position between the two end points will also occur twice in each amplitude cycle producing two low tension extremes. This will result in there being two tension cycles that correspond to each amplitude cycle (Figure 3). In terms of frequency, the theoretical tension frequency should be twice the theoretical amplitude frequency.

Tension and displacement time histories were analysed for frequency content using power spectra [2] and response spectra [18] analysis techniques. Power spectra analysis is a technique used to determine the dominant frequencies in a random stationary time history. Data is considered stationary when the mean of the data is constant or changes very slowly with time. A power spectrum obtained from a time history of cable tension or spar movement will have a peak value at the predominate frequency contained in the record. For structures excited by plucking, the predominant frequency is the natural frequency of oscillation for the structure. The discrete Fourier Transform necessary for spectral analysis was accomplished using a digital computer program containing the Fast Fourier Transform (FFT) developed by Cooley et al. [7].

Response spectra analysis is a technique common in the analysis of structures subjected to earthquake loadings [18]. A response spectra is the maximum response of a one degree of freedom damped structural system to the dynamic excitation of concern over a range of system natural frequencies. A plot of a response spectra will show a peak at the system natural frequency that coincides with the predominant frequency of the dy-

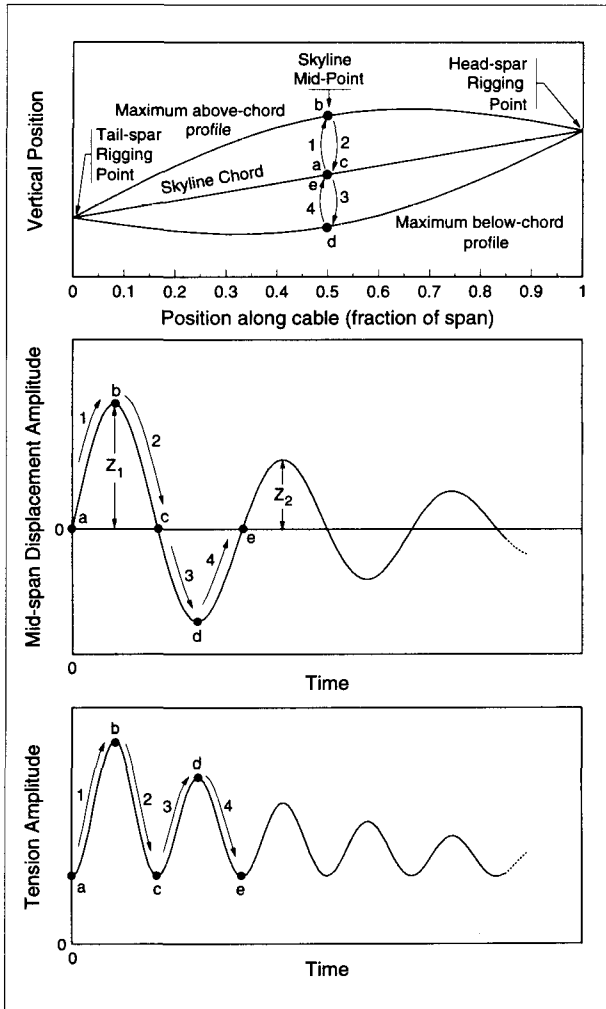


Figure 3. Correspondence between tension and displacement amplitude time histories in a taut vibrating cable.

dynamic excitation. Response spectra computations were accomplished using a published digital computer program [11].

In general, response spectra analysis was used for records that were non-stationary, or of too short a duration to contain sufficient repetition of the frequencies for standard power spectra analysis, and power spectra analysis was used for relatively long duration stationary records. Skyline tension and spar movement records from all the tests were analysed using response spectra, guyline tension records from the logging tests were analysed using response spectra, and guyline plucking test records were analysed using power spectra.

System Damping

Damping in cable systems is usually formulated as a viscous component in the equations of motion that describe the system. It is expressed as a percent of critical damping, and can be calculated using the log decrement procedure [6]. The source of cable damping has been reported to be (1) rubbing between the strands of the cable, (2) air resistance to cable motion (usually negligible), and (3) work done on the cable supports which are never completely rigid [8]. Irvine [8] reports that cable damping is small, usually less than one to two percent, but in some cases can be as high as four percent (this latter case being one with relatively flexible supports).

The equations of motion for which the standard log decrement procedure for obtaining damping apply are written in terms of displacements, not cable tensions as were measured during the field tests. This requires some interpretation of the field data to obtain the standard damping values for the cables. As shown in Figure 3, two cycles from a tension versus time plot correspond to a one cycle from an amplitude versus time plot. For a linear elastic cable, the log decrement for a single cycle of amplitude versus time will then be the value obtained from the two cycles of the tension versus time plot. A cable is not normally a linear elastic element, but if the cyclic variation in tension is small relative to the ambient tension, then the cable behaviour will be nearly linear.

The log decrement and resulting percent of critical damping are obtained from the equations [6, 17]:

Logarithmic Decrement,

$$\delta = \frac{1}{n} \ln \left(\frac{z_1}{z_{1+n}} \right) \tag{2}$$

Percent of Critical Damping,

$$D = \frac{1}{\sqrt{\left(\frac{4\pi^2}{\delta^2} + 1 \right)}} \cdot 100\% \tag{3}$$

where: n = Number of displacement amplitude cycles between peaks

z_1 = Displacement amplitude of the first peak

z_{1+n} = Displacement amplitude of the peak " n " cycles following.

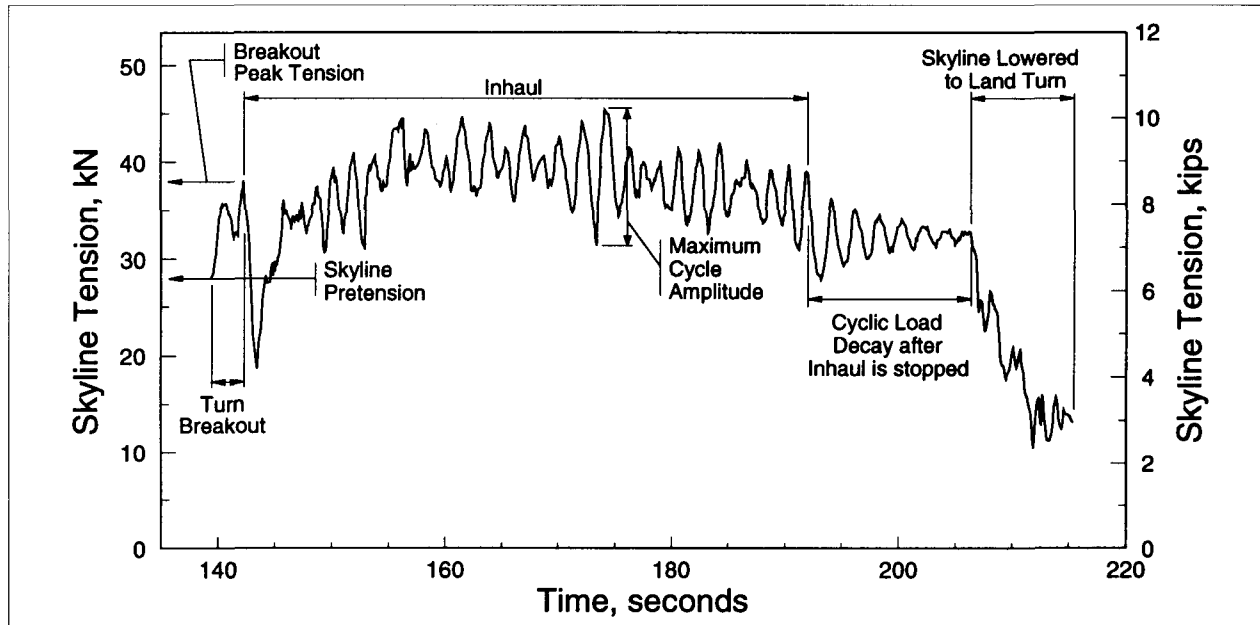


Figure 4. Characteristics of the Skyline tension during the full inhaul portion of the yarding cycle.

Use of the log decrement procedure requires identification of distinct sequential cycles in the tension of a cable that has a stationary ambient tension value. This was easily done for the skyline, but could not be done for the guylines because of ambient tension variations associated with movement of the spar.

Damping of the tailspar was obtained more directly from the records of spar-top displacement using the logarithmic decrement procedure. However, this procedure provides only a rough indication of damping levels because of the potential for transmission of energy from one plane of motion to another. The displacement measurements were taken in two orthogonal planes. The tailspar was set in motion by pulling the spar off centre and then releasing it to oscillate. The direction of pull was always more in one of the planes of measurement than the other, so often, the initial motion was in the plane most in-line with the direction of pull, but as this motion decayed, motion in the transverse plane increased, or at least was sustained for a greater number of cycles.

Dynamic Load Magnitude

The instrumentation system (Figure 2) included skyline tension for each yarding test, but was re-configured to include mainline tension on only four

tests. Mainline tension was included on a limited number of tests because the load cell and signal cable necessary to obtain mainline tension did not allow full inhaul of a turn. For this reason, it is the skyline tension records from the yarding tests that provided an indication of dynamic load magnitude. Two types of dynamic load magnitudes were extracted from the skyline tension records. First, the “break-out” peak tension associated with starting the turn moving, and second, the maximum cyclic tension amplitude following breakout were obtained from all the yarding test records (Figure 4).

RESULTS

Frequency content

The natural frequencies extracted from test measurements compare quite well with theory for the first natural frequency of the guylines, but not for the skyline (Figure 5). This can be explained by the fact that guylines are simple cable segments that only depart from theory in the slope of the guyline. The skyline on the other hand has two characteristics that do not correspond to simple cable theory. The carriage on the skyline (approximately 0.78 kN [175 lbs]), which is of the same order in weight as the weight of the skyline (approximately 1.0 kN [220 lbs]), added additional mass to the vibrating system altering the natural frequency of the skyline. Fur-

ther, the ends of the skyline are not points of longitudinal fixity as assumed in simple cable theory. The skyline passes through blocks on both the headspar and the tailspar, resulting in the longer cable length than the skyline chord length. Since both cable length and mass are in the denominator of the theoretical frequency relationship (Equation 1), it should be expected that the carriage mass, and the additional cable length would work to lower the natural frequency. Indeed, the values of natural frequency extracted from the field data are lower than the theoretical values. However, the amount by which the skyline natural frequency should be less than simple cable theory cannot be determined without deriving a new basic theoretical relationship for natural frequency with the correct boundary conditions of a skyline.

The first natural frequency of the tailspar was obtained from the spar top movement in the line of the skyline corridor during five sets of free vibration tests. Confirmation of the first natural frequency was made by examining the deflected shape of the spar to insure that higher modes were not being considered. In a few of the tests, higher mode vibration was evident for the first second or two of the record, but was quickly damped out and followed by an extended period of free vibration at the first natural frequency. Table 2 provides a description of the test sets, and Figure 6 summarizes the results.

The results from the five sets of tests are dramatically different, and shed some light on the structural complexity of a cable logging system. The natural frequency interpreted from the free vibration tests varies with skyline tension in a consistent manner. If the spar-tree system is viewed as a simple, single degree of freedom, undamped oscillator, then the governing equation for natural frequency would be [17]:

Undamped Natural Frequency,

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \tag{4}$$

where: k = System stiffness
 m = System mass.

Increases in skyline tension will result in deflection of the spar-tree and increased tension in the rear guylines of the spar-tree. Since the guylines have nonlinear stiffness that increases with increased tension [12], the system stiffness will increase with

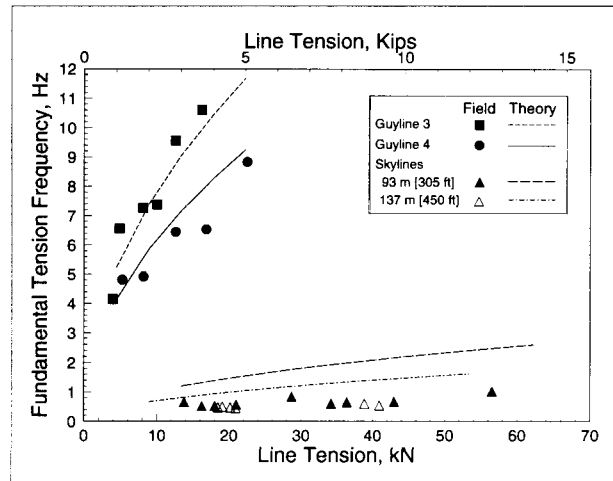


Figure 5. Skyline and guyline first natural frequencies.

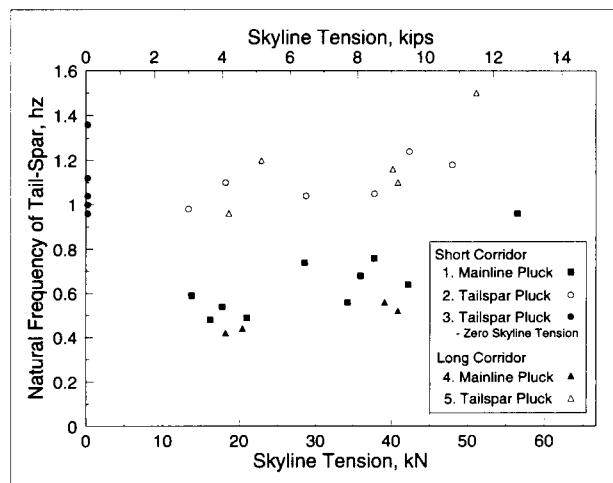


Figure 6. First natural frequency of the tailspar as interpreted from displacement time-histories during free-vibration tests.

increased skyline tension. From equation (4) above, it can be seen that this should result in an increase in the natural frequency as evident in the test results (Figure 6).

Some additional comment is required for the results from test set 3. Skyline tension was zero for all these tests, but guyline tensions and the order of tightening were varied within tension values attainable by hand tightening. The different orders of guyline tightening and tension values would have resulted in a range in spar-tree stiffnesses that would be expected to produce a range in natural frequency.

Table 2. Test conditions for the natural frequency of the tailspar.

Test Set	Skyline Tension,kN [kips]	Skyline Length,m [feet]	Method of excitation
Short Corridor			
1. Mainline Pluck	13.8 - 56.5 [3.1 - 12.7]	93 [305]	Pull and release the mainline.
2. Spar-Tree Pluck	0 - 48 [0 - 10.8]	93 [305]	Pull and release the top of the spar.
3. Spar-Tree Pluck -zero skyline tension	0	93 [305]	Pull and release the top of the spar. -guyline tension and tightening order was varied.
Long Corridor			
4. Mainline Pluck	18.2 - 40.9 [4.1 - 9.2]	137 [450]	Pull and release the mainline.
5. Spar-Tree Pluck	18.7 - 51.2 [4.2 - 11.5]	137 [450]	Pull and release the top of the spar.

However, the five tests conducted were insufficient to identify a pattern. These results can none-the-less be viewed as an example of the variation in natural frequency that can occur with normal variation in the spar-tree rigging process.

System Damping

Values of percent of critical damping are listed in Table 3. The skyline values included evaluations from the free vibration portions of logging tests (Figure 4), as well as the tests of free vibration used to obtain natural frequency. The skyline values are much higher than the published ranges, but as indicated in the section on frequency, the skyline system has flexible end-points, and therefore should be expected to exhibit much higher damping than from the cable alone [8]. Damping for the tailspar guylines could not be determined due to noise in the tension records. The noise, most likely due to dynamic behavior in the tailspar and the skyline, obscured the individual cycles in the record, without which the logarithmic decrement cannot be determined. The spar-tree damping values are similar to published values for wood structures at stress levels between 0.5 to 1.0 times the yield point of the materials [9].

Throughout the range of all the tests, the variability in damping was very large as indicated by the

large coefficients of variation given in Table 3. No systematic variation in damping was evident in the test results.

Although distinct values of damping can be obtained by the logarithmic decrement procedure, it must be remembered that the system was fully rigged in all cases, but in a few, the skyline was slack (zero tension). This means that the skyline was participating in the free vibration tests of the tailspar, and vice versa. It should be expected that including the skyline in a free vibration test of the tailspar would offer increased opportunity for radiation damping that would result in higher damping values from the logarithmic procedure. The same is true for free vibration tests of the skyline.

Dynamic Load Magnitude

Dynamic load magnitude expressed in relation to turn weight and/or skyline tension is possibly the most valuable parameter that a series of dynamic logging tests could produce. In the absence of dynamic load magnification, dynamic load increment added to static load yields the total system load that individual components of a cable system must be designed to withstand. Static load can be reasonably predicted by numerical computations that consider skyline profile, turn weight, carriage clearance, line

Table 3. Results of damping evaluations from free vibration tests.

System Component	Average Logarithmic Decrement	Percent of Critical Damping	
		Average	Coefficient of Variation
Skyline	0.662	10.5%	0.42
Spar Tree	0.575	9.15%	0.36

sizes, and tailspar and tower height [10]. If the likely dynamic loads can be characterized from dynamic logging tests of the type reported here, then maximum expected line tensions could be estimated.

The two types of dynamic loads extracted from the logging test data are summarized in Table 4. The dynamic loads are expressed as absolute values, and factors in relation to skyline tension. These measures of dynamic load magnitude are intended to reflect the general character of the system and the stand from which the log turns were extracted. There was not a sufficient number of tests for the load magnitudes to indicate trends with turn location, turn size, inhaul speed, or other parameters that may also influence dynamic load magnitude. However, it is apparent from the data that dynamic loads can be quite variable. This is most apparent for the tests with artificial breakout resistance on turns of a variety of sizes, and the case of the maximum cyclic load from the series of logging tests run with the same two-log turn.

The manila rope that was used to provide the artificial breakout loads had a relatively constant breaking strength that produced a breakout load of approximately of 10.7 to 13.3 kN [2,400 to 3,000 lbs] at the turn. This relatively constant artificial breakout resistance, in conjunction with the natural resistance present, produced a skyline tension increase with a coefficient of variation of 79%.

The tests run with the same two-log turn were done to determine the variability in dynamic load that should be expected from a single turn. The difference in the cyclic load from test to test with this same turn would have to be associated with differ-

ences in the exact pattern of surges and bumps that the turn experienced during inhaul. The opportunity for the turn to encounter obstacles along the corridor was relatively constant from test to test, but there would be normal variations in the operation of the yarder. This relatively consistent test setting resulted in a coefficient of variation in maximum cyclic load of 39%. If the maximum cyclic loads are normalized to skyline tension (Table 4), the coefficient of variation is only slightly reduced to 31%.

If we compare Maximum Cyclic Load Amplitude Factor (Table 4), the coefficient of variation from the 9.12 kN [2,050 lbs] two-log turn tested a number of times (31%) is only modestly less than the coefficient of variation from tests on a variety of turns yarded at different skyline tensions (36%). A further view into dynamic load variability is given in Figure 7 which shows the relationship between skyline tension and maximum cyclic load amplitude for the 9.12 kN [2,050 lb] two-log turn. There appears to be a positive correlation between skyline tension and cyclic load, but the scatter is broad, and appears to increase with increasing skyline tension. It is questionable if a regression equation to describe this relationship would be of value.

Total System Behaviour

As indicated above, the limited number of logging tests conducted was not sufficient to characterize dynamic loads. However, from even a few logging tests, it is possible to gain an understanding of some basic factors about the response of a cable logging system to dynamic loads. The results from two logging tests will be used for illustration.

Table 4. Dynamic skyline load magnitude.

Dynamic Load Type	Average Value	Coefficient of Variation	Sample Size	Notes
Natural Breakouts				
Breakout Tension Increase ^a	12.6 kN [2.84 kips]	56%	19	Turn weight: 1.51 to 9.12 kN [340 to 2,050 lbs]
Breakout Tension Factor ^b	0.47	79%	19	
Artificial Breakouts				
Breakout Tension Increase	14.1 kN [3.16 kips]	66%	13	Turn weight: 2.54 to 9.12 kN [570 to 2,050 lbs]
Breakout Tension Factor	0.46	76%	13	
Maximum Cyclic Load Amplitude^c				
-from all tests	13.6 kN [3.07 kips]	40%	38	Turn weight: 1.51 to 9.12 kN [340 to 2,050 lbs]
-from tests with the same 9.12 kN [2,050 lb], 2 log turn	13.3 kN [2.98 kips]	39%	19	
Maximum Cyclic Load Amplitude Factor^d				
-from all tests	0.36	36%	38	Turn weight: 1.51 to 9.12 kN [340 to 2,050 lbs]
-from tests with the same 9.12 kN [2050 lb], 2 log turn	0.36	31%	19	

^a Breakout Tension Increase = Peak Breakout Tension - Skyline Pretension
^b Breakout Tension Factor] = $\frac{\text{Peak Breakout Tension} - \text{Skyline Pretension}}{\text{Skyline Pretension}}$
^c Maximum Cyclic Load Amplitude = greatest peak to peak change in skyline tension in a single cycle.
^d Maximum Cyclic Load Amplitude Factor = $\frac{\text{Maximum Cyclic Amplitude}}{\text{Skyline Pretension}}$

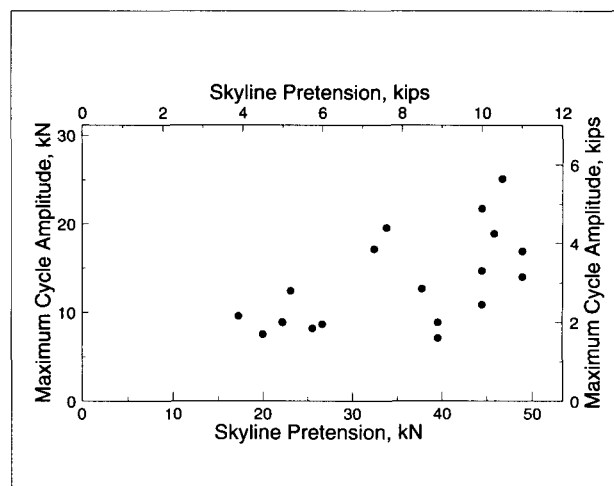


Figure 7. Maximum cycle amplitude variation for the same turn yarded over the same corridor at varying skyline tensions.

Results from Test 6 are illustrated in Figure 8 (also see Figure 4). The turn being yarded weighed approximately 4.45 kN [1,000 lbs], and the carriage was spotted at about the 40% point between the tailspar and the headspar. This carriage position would require the turn to pass the mid-span point during inhaul shortly after the carriage released from the skyline stop. Theory would indicate that the maximum static skyline tension from a given load should occur when the turn is at about mid-span. It can be seen from the skyline tension plot (Figure 8a) that the line describing the average skyline tension does in fact reach a peak shortly after inhaul begins. The tailspar principle guyline tension (Figure 8b) and spar-top movement (Figure 8c) show similar behaviour. This should be expected since the spar load comes from the skyline.

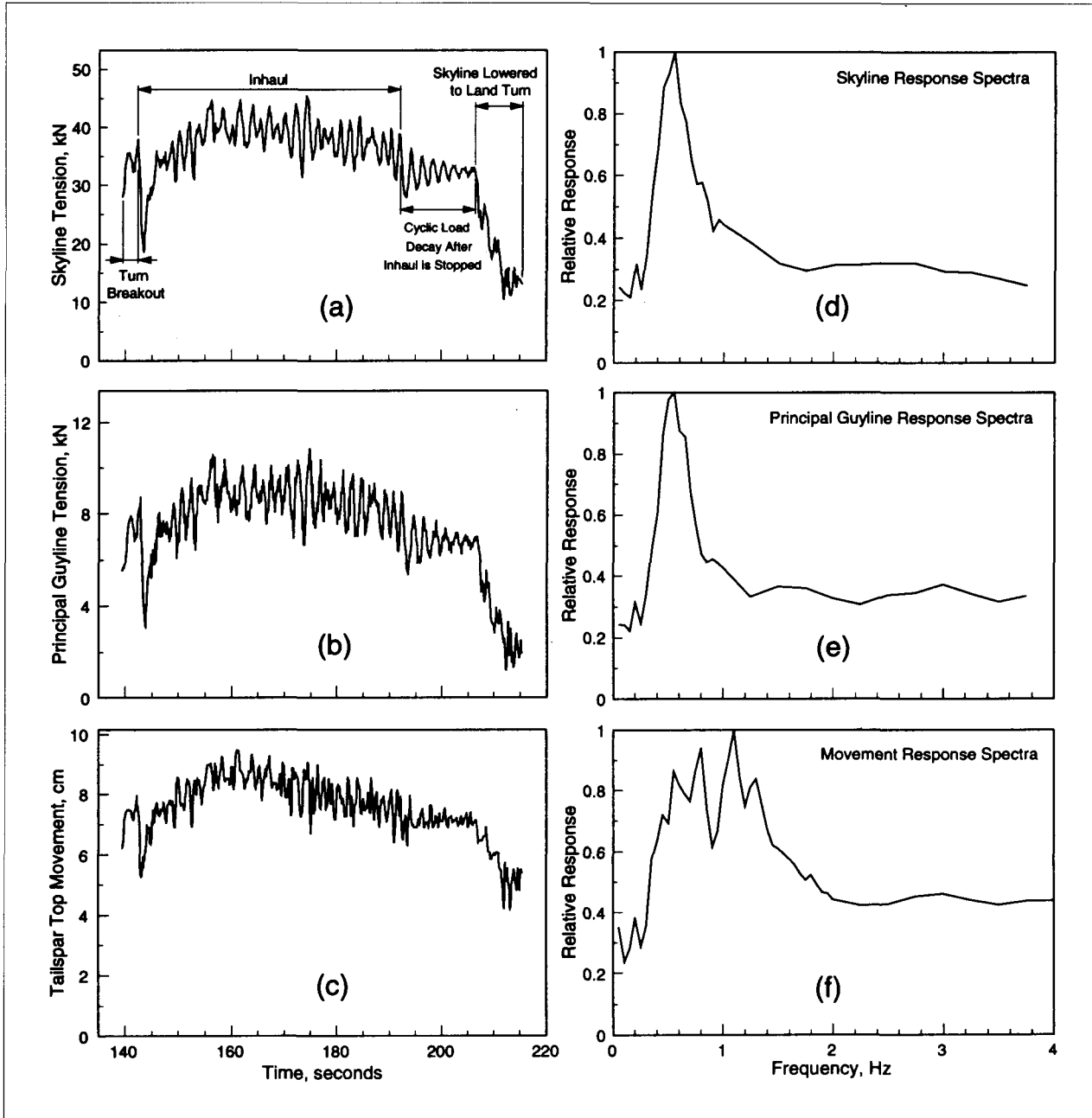


Figure 8. Dynamic test results from the full inhaul portion of yarding Test 6.

Examination of the frequency content of the cyclic load and movement patterns indicates a somewhat more complex pattern. The skyline and principle guyline tension records have very similar frequency content. This is illustrated in Figures 8d and 8e in the response spectra for the two records. The predominant frequency in both records is 0.55 Hz. The guyline tension record contains more high frequency components, as evidenced by the sharp nature of the peaks in the tension record, but the

magnitude of these higher frequencies is not large as indicated by only a modest difference in the response spectra at higher frequencies.

The spar-top movement record shows something quite different. The response spectra indicates a broader frequency band of high response in the record (Figure 8f). There is still a peak in the response spectra at 0.55 Hz which is the predominant frequency of the forcing function (the forcing function

for the spar is the skyline tension), but there are other equal or greater peaks at 0.8, 1.05, and 1.15 hz. These other peaks represent the response of the tailspar to a lower frequency forcing function. The reason for these response peaks is that a structure responds the greatest at its natural frequency. Interpretations of the natural frequency of the tailspar included frequencies on the order of 1.0 hz, hence the strong response in this frequency range. The reason that the guyline tension does not exhibit identical response to the tailspar is that the principal guyline was not in the plane of the skyline in which spar movement was measured.

Test 6 presented above was selected because it includes the full inhaul portion of the yarding cycle. Test 35 was conducted with a load cell in the mainline between the carriage and the turn. This has the advantage that the magnitude of breakout forces and hang-ups during inhaul was recorded, but the wiring of the load-cell prevented yarding all the way to the landing such as in Test 6. The turn for test 35 was approximately 4.45 kN [1,000 lbs]. The turn broke free with only a modest breakout peak load, but encountered a hang-up during inhaul that produced a sharp peak load in the mainline (Figure 9).

Test 6 showed that a narrow banded forcing function in the skyline can excite other frequencies in the tailspar. Test 35 shows that the skyline serves as a filter for a very broad band of frequencies in the main line, preventing them from reaching the other components of the system (Figure 9). The mainline tension record includes equally strong frequencies from 1.5 hz to 4.5 hz. Yet the skyline responded only to its natural frequency of about 0.5 hz. The principal guyline shows nearly the same frequency response as the skyline because the natural frequency of the guyline is on the order of 5 to 10 hz, and these frequencies are not present in the skyline tension record which transmits the dynamic loads from the mainline to the tailspar and guylines. There is some indication of higher frequencies being present in the guyline tension record between 654 seconds and 660 seconds, but the higher frequency component is not very strong. The tailspar shows a similar peak response at about 0.5 hz, but also shows significant response at 0.75 and 1.5 hz indicating that the skyline tension frequencies were near enough to the natural frequencies of the tailspar to cause the spar movement to contain those frequency components.

SUMMARY

A series of tests for the purpose of determining the dynamic properties of a short-span skyline cable logging system allowed the determination of natural frequencies and damping values for the system components. The observed natural frequencies of the tailspar guylines agreed closely with theory, while the skyline natural frequencies were significantly different than theory. However, changes in natural frequency as a function of line tension were consistent with theory. Tailspar natural frequency varied with system stiffness in a manner consistent with a simple, single degree of freedom, damped oscillator, but the absolute value of natural frequency is confounded by the source of the forcing function.

Damping values for the tailspar and the skyline were both in the range of 10%. The skyline value is higher than might be expected for a simple cable, but not for a cable that is part of a larger structural system. The damping interpreted from the tailspar records is similarly larger than should be expected for a simple cantilever structure, but given that the structural system included the skyline, etc., it appears reasonable. Damping for the tailspar guylines could not be determined due to noise in the tension records that was most likely due to dynamic behaviour in the tailspar and the skyline.

The yarding tests of the full system showed that the magnitude of dynamic loads is highly variable. This suggests that for the full range in cable logging system sizes and harvest unit sizes and layouts, a rather exhaustive series of dynamic load measurements would be necessary to fully describe the average dynamic load and variability of the load that might be expected for a given instance. The yarding tests also showed that the skyline is a very effective filter for the dynamic loads that the other components of the system will experience. In practical application, this would mean that rigging the tailspar and tower so as to have significantly different natural frequencies than the skyline would preclude a resonance condition occurring even if the frequency of the dynamic load from the turn coincided with the natural frequency of the tailspar or tower.

The results of this study suggest that dynamic load magnitude cannot be effectively described with averages, but rather should be represented by an upper-bound envelope. An upper bound envelope would allow simple pseudo-static analysis, wherein

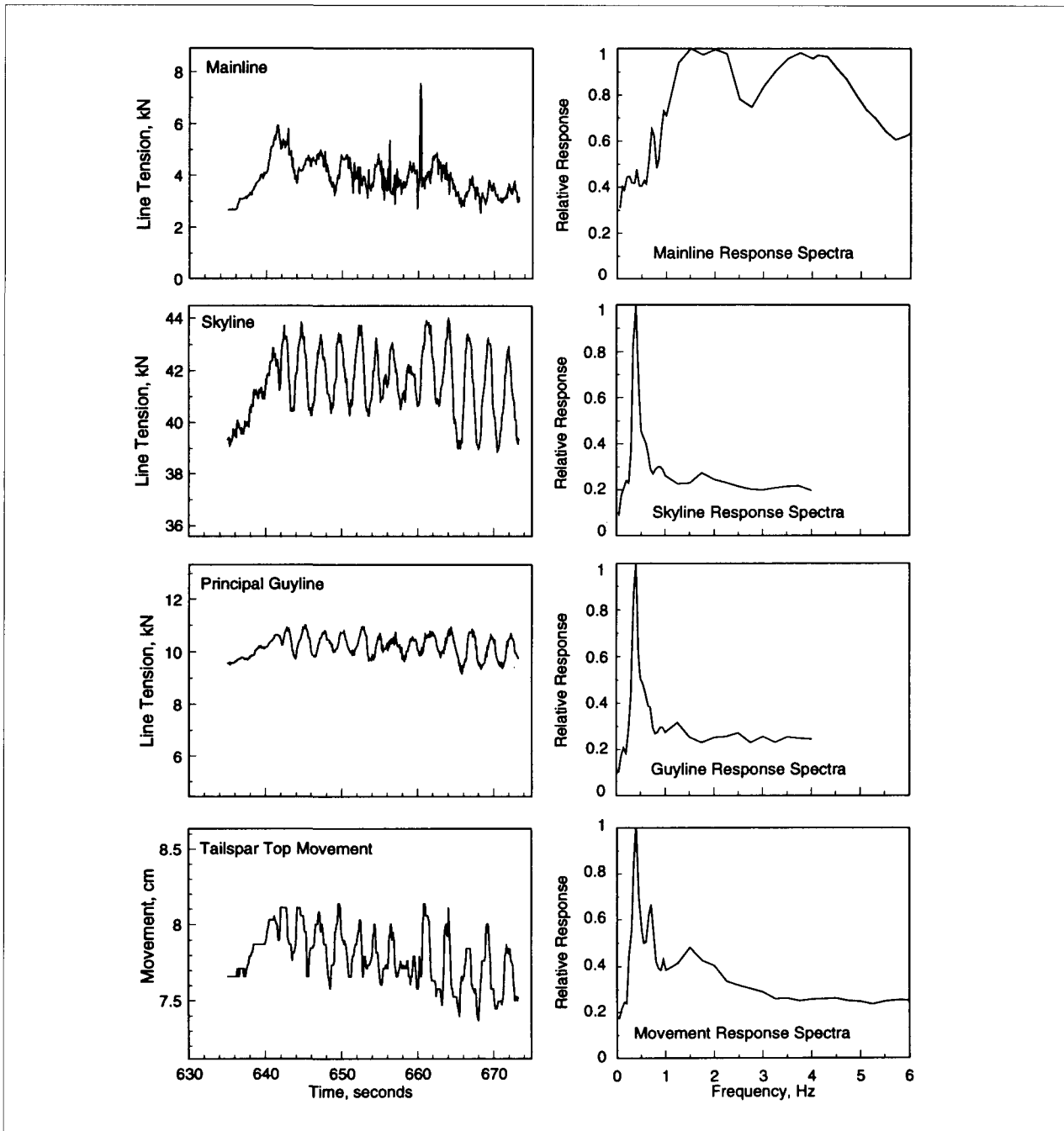


Figure 9. Dynamic test results from yarding Test 35 which included measurement of mainline tension.

the dynamic loads are simply added to the static loads, to be an effective tool for determining safe cable logging system loads. In cases where possible resonance was a concern, the use of a full dynamic model would have to be employed.

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