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Tension Monitoring of Cable-assisted Felling Machines

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EXECUTIVE SUMMARY

Cable-assisted tree felling systems are becoming more common in New Zealand as companies strive to mechanise harvesting operations on steep terrain. The current Approved Code of Practice for Safety and Health in Forest Operations (ACOP) requires operators to manage wire rope tensions so that the tensions do not exceed 33% of breaking load. To improve the forest industry's understanding of both wire rope tension and shock loads during operations, tension monitoring tests were carried out on three different cable-assisted felling operations.

Results clearly indicated that the loading on the rope was not constant, and through a time and motion study the shock loads induced were clearly linked to the movement of the machine. Work activities such as felling, shovelling, or operating on different slopes, had a negligible effect on tensions recorded. Tensions recorded during work activities reflected the tension setting selected by the operator. While shock loading was frequent and relatively large (at up to approximately 70% above the base tension) it was very consistent and predictable when the machine was moving.

In addition to the need for operators to understand these tension characteristics of their machine, the intent of these tests was to also provide manufacturers of cable-assisted machines with feedback to improve tension management in future machine designs. As a result of this study, it is recommended that contractors in the New Zealand logging industry operating cable-assisted systems should give serious consideration to incorporating continuous tension monitoring technology that will allow them to review and act upon operational data.

INTRODUCTION

The primary goal of the Future Forests Research Ltd (FFR) Steep Land Harvesting Programme is to reduce costs and improve worker safety in steep land harvesting, by increasing the productivity and efficiency of these operations. Cable-assisted felling machines for timber harvesting are not new and have been commercially available in Europe since the early 1990s (Visser and Stampfer 2015). In New Zealand the first designed applications of cable-assisted machines were in the Nelson region. Contractor Ross Wood is credited with running the first designed cable-assisted operation, while Nigel Kelly of Kelly Logging Ltd, together with Trinder Engineering Ltd of Richmond, Nelson, supported by FFR, designed and built the first purpose-built commercially available machine; the 'ClimbMAX Steep Slope Harvester' (Evanson & Amishev 2009).

The development of cable-assisted machines in New Zealand has seen the emergence of a number of different system variations. One fundamental difference is the location of the winch, either on the machine that is operating on the slope, or on a separate machine that serves as the anchor. These systems can be referred to as either dynamic (Figure1A) or passive systems (Figure 1B) depending on the movement of the winch rope during operation (Ellegard 2015).

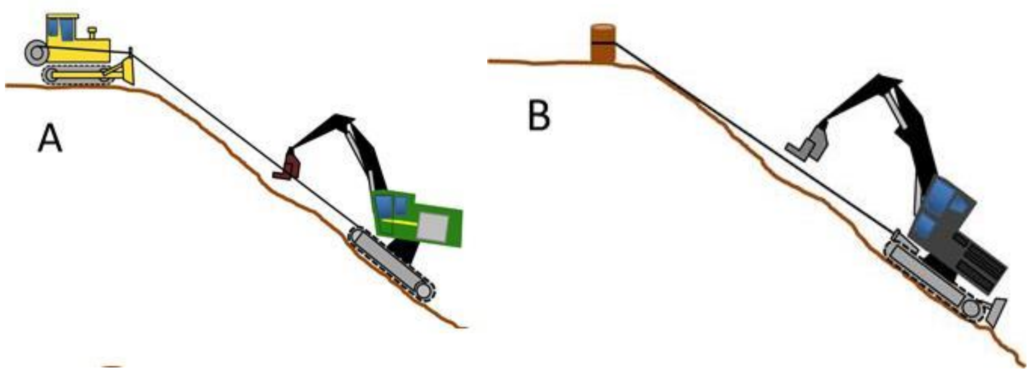


Figure 1: Concept of dynamic (A) and passive (B) systems developed for New Zealand steep terrain harvesting.

The difference between the two is that the passive system has the winch integrated into the felling machine undercarriage and pays out rope as the machine descends the slope, while the dynamic system has the winch mounted on a separate machine (such as a bulldozer or excavator) which winches the rope in or out as the felling machine ascends or descends the slope. Each system has unique advantages and disadvantages, discussed by Visser (2013) and Visser and Stampfer (2015). These are summarised in Table 1 overleaf:

Table 1: Advantages and disadvantages of the two winch-assist systems

	A. Dynamic Winch Assist System	B. Passive Winch Assist System
Advantages	• Winch assist machine is readily connected to, and disconnected from, any felling or bunching machine • Winch assist machine is mobile and can readily be moved • Power requirements for winching and felling/bunching tasks are split between two machines	• Single machine 'system' • Less rope wear as it is not moving across the ground • Does not require machine access to back line/top of hill
Disadvantages	• System requires two machines, and communication between them for effective winch operation • Requires access to the back line/top of hill for winch machine • Potential for more rope abrasion, as rope moves (cutting in to the ground and/or stumps used to re-direct the rope)	• Higher capital cost felling machine • Winch is integrated so cannot be used with other felling machine • Requires suitable anchors such as stumps, deadmen or mobile tail hold machine • Adding a winch system both adds weight and increases power requirements for winching, track movement and felling/bunching functions

Cable-assisted felling can improve both safety and productivity (Evanson & Amishev 2009), as well as increasing the operating range of ground-based systems (Visser and Stampfer 2015). Visser (2013) has described how cable-assisted machines are able to traverse steep terrain through increased stability and by overcoming traction limitations. A recent survey showed that such machines are now commonly available and are quickly increasing in popularity in New Zealand, with more than 40 in operation by the end of 2015 (Raymond 2015). Earlier research work has assisted developers of cable-assisted machinery. Visser (2013) measured the tensions of one of the first prototype machines, while another study evaluated the productivity, soil disturbance, ergonomics and cable tensions of the first purpose-built machine that was commercially available in New Zealand (Evanson & Amishev 2013).

One of the most important issues affecting the safety of these machines (and potentially the uptake of this technology) is the tension in the operating winch rope(s). Tensions in the winch rope(s) must be within allowable limits (e.g. safe working load, endurance limit and elastic limit) when the machine is operating (both felling and moving across the slope) to avoid excessive wear and possible rope failure.

The safe working load (SWL) is an important design and operational factor in harvesting operations which is dictated by the wire rope type and dimensions, and also possibly the related connections / fittings used. The SWL is an important measure, and was designed from the perspective of wire rope properties to maximise rope life. Accelerated damage starts to occur when then tension is above 50% of breaking strength (referred to as the 'endurance limit'), and immediate damage occurs at about 65% of breaking strength (referred to as the 'plastic' or 'elastic limit').

In New Zealand forest operations, SWL is defined as $^{1}/_{3}$ (or 33%) of the wire rope's breaking strength (MBIE 2012). The current Approved Code of Practice for Safety and Health in Forest Operations

(ACOP) covers the operation of cable-assisted machines in New Zealand. One of the requirements is that the tension in the winch rope(s) must never exceed 33% of breaking strength (SWL).

Tension Monitoring

Most previous research on cable tensions used in forest operations has been for cable logging, and is summarised in the recent literature review by Harrill and Visser (2014a). Dynamic cable tension monitoring has been described by Carson and Jorgensen (1978) and Pyles (1988), noting that static tensions calculated by simple theoretical equations are rarely corroborated in real operations. Ways that dynamic tensions could be recorded and how to model them have been identified (Carson *et al.* 1982; Kroneberger-Stanton and Hartsough 1992; Lyons 1997; Pyles *et al.* 1994; Womack 1994). The tension and shock type loading behaviour of some logging systems has been investigated by Visser (1998) and Miles *et al.* (1993), and tension monitors were found to provide results and benefits to contractors (Hartsough 1993; Smith 1992). As such, most cable tension research has been related to either skylines or guy lines rather than working ropes (mainline or tail rope).

Harrill and Visser (2014b) measured and compared skyline tensions of different cable rigging configurations used in New Zealand. The authors found that the SWL of the skyline was exceeded often – at seven of eight operations studied and during 53% of all carriage cycles recorded. Conclusions from the study suggested that the forest industry should give serious consideration to the use of tension monitors in cable yarding as they have many useful applications to improve operations. For example, monitoring tensions can be used to help ensure safe use of wire ropes, evaluate alternative techniques and train new operators, and to extend the working life of the rope. As such, this knowledge should be extended to cable-assisted technology, as similar loadings can be expected.

Only two previous studies in New Zealand have investigated wire rope tensions of cable-assisted machines, with differing results. Visser (2013) studied a dynamic system and found that while the machine operated within the SWL limits of the wire rope, it was possible to exceed the SWL. Evanson and Amishev (2013) studied a passive system and found that the SWL was only just exceeded on a few occasions for a few seconds during machine movement.

The main manufacturers of winch-assisted machines (ClimbMAX Equipment Ltd, EMS Ltd, DC Equipment Ltd and Rosewarne and May Ltd) all measure tension of the winch rope, but use different methods. None of these systems currently has data logging (recording) capability. Both the ClimbMAX Steep Slope Harvester and the EMS Tractionline measure line tensions through the winch hydraulics. The DC Equipment Ltd Falcon winch-assist machine measures tension through the pin on the sheave. The Remote Operated Bulldozer (ROB) from Rosewarne and May Ltd uses deflection of the rope through three sheaves. Some other independent manufacturers have put load-cells between the felling machine and the connection to the rope (i.e. in the drawbar). Other contractors operate their machines with the winch calibrated, but without ongoing tension monitoring during operations. While new cable-assisted systems are designed to avoid overloading, no independent testing has yet been carried out to improve our understanding of tensions, and the possible reasons for high tensions in these new systems.

METHOD

Objectives

The objectives of the study were to:

1. Monitor tensions of operating cable-assisted felling systems.
2. Improve understanding of cable tension behaviour during all phases of mechanised felling operations.

Study Sites

Three cable-assisted systems from different manufacturers were studied during normal operation:

- Rosewarne and May Ltd's Remote Operated Bulldozer (ROB)
- Ross Wood's original design, now operated by Brand Logging Ltd
- Independent design by Bill Winmill of Gillion Logging Ltd, now operated by Button Logging Ltd.

Characteristics associated with each site such as soil type, aspect, slope and terrain roughness were measured. In one study a GoPro camera was used to continuously record the tension output, as displayed on the in-cab screen at 5 Hz intervals, from the integrated tension monitor. At the other two sites running line tension monitors (Figures 2 and 3) were used to record data at 10 Hz directly into a computer.

Figure 2: Running line type tension monitor that allows movement of wire rope during operation.

Figure 3: Built-in running inline tension monitor attached to the back of the dozer blade.

The running line tension monitor was calibrated in a mechanical engineering workshop up to 20 tonnes, and readings higher than that are indicative only. During the tension monitoring data recording a basic time study, including work task and machine movement, was also carried out. Photos and video footage were captured at the same time. This study is mainly concerned with understanding the general behaviour of these systems and it is not intended to be used to compare the performance of the different cable-assisted machines tested.

Cable-Assisted Felling Systems Measured

Configuration A: This was a double winch system mounted at the rear of a 21-tonne Liebherr 734 bulldozer with two 22mm ($^{7}/_{8}{}^{th}$ inch) swaged wire ropes attached to a John Deere 909KH harvester with a Southstar felling head. A twin chain was used to connect the harvester to the wire rope, with an equalising block connection between the chain and rope (Figure 4).

Figure 4: John Deere 909KH harvester and Liebherr 734 bulldozer anchor with double winch cable-assisted system.

In this system both winches pulled in / let out the cables at the same rate, with the equalising block allowing the harvester to move side-to-side without overloading one of the cables. The tension monitor was built into the bulldozer; it used a running inline monitor which was attached to the blade on the front-right corner of the machine.

Configuration B**:** This was a single winch mounted on the back of a 25-tonne Komatsu bulldozer with a 28mm ($1^{1}/_{8}{}^{th}$ inch) swaged wire rope attached to a CAT 3250 excavator with a Satco harvester head. A relatively new feature was a structural frame addition to the undercarriage (a custom built draw bar) which extended out slightly past the tracks where the hitch was mounted. The winch cable was attached to a section of heavy chain, which in turn was connected by a shackle to the hitch (Figure 5).

Figure 5: New hitch support frame, cable-assist unit and anchor (bulldozer based) showing winch unit on back (right), assisting the harvester (Cat 3250).

The winch had settings that the operator of the harvester selected via remote control. These settings related to a pre-set speed (in rpm) on the bulldozer which varied the power to the winch. The bulldozer was positioned on a purpose-built track that facilitated access to the top of the stand. The soil type for the whole hillside was very dry gravelly silt.

During the testing period the harvester travelled 150 metres down the track, and then used a tree ('rub tree') to turn downslope to the right at a 90-degree angle to the track (Figure 6). It would then fell and shovel trees down to a road about 300 metres below. The slope on which the machine operated ranged from 30 to 40 degrees.

Figure 6: "Rub tree" with 5cm deep gouge from cable.

Configuration C: This was a single winch mounted at the rear of a 42-tonne Hitachi ZX380 excavator with a 28mm ($1^1/_8{}^{th}$ inch) swaged wire rope attached to a Madill HT2200B self-levelling harvester (Figure 7). The winch unit on the excavator used a hydraulic cam system which allowed the cable drum to pivot back and forward under load. The position of the winch unit would either engage or disengage a band brake on the drum.

The brake engaged during stationary work phases, allowing the engine to stay idle while the length of cable paid out remained constant. The winch had four power settings; three were pre-set rpm settings and the fourth was a manual override, giving the operator complete control of the engine powering the winch.

The rope was connected to a length of chain attached to the harvester. The excavator itself was positioned on a relatively flat piece of ground at the top of the hill with its boom extended and bucket buried to approximately $^1/_3$ of its depth to provide stability. The slope immediately in front of the excavator was 30 degrees, and the harvester operator reported that this slope increased to 40–45 degrees for the slope on which the machine operated. The soil type on the slope was a shallow loam over a dry gravelly silt substrate.

Figure 7: Hitachi excavator with pivoting winch, assisting the Madill HT2200B harvester.

RESULTS

Tension Measurement

The results presented are 25–30 minute segments of each tension data set collected during periods of normal working activity at a minimum sampling rate of 5 Hz.

Configuration A: Although this was a two-rope system, the tension measured during this study was recorded for one rope only. Assuming that the forces on both sides were equal, the overall cable-assisted effort would be double that recorded. The typical response of the system is displayed in Figure 8. Base tensions were around 4, 8 and 12 tonnes, which likely corresponded to the different winch power settings. Tension spikes tended to be around 5-10 tonnes in magnitude above base tension.

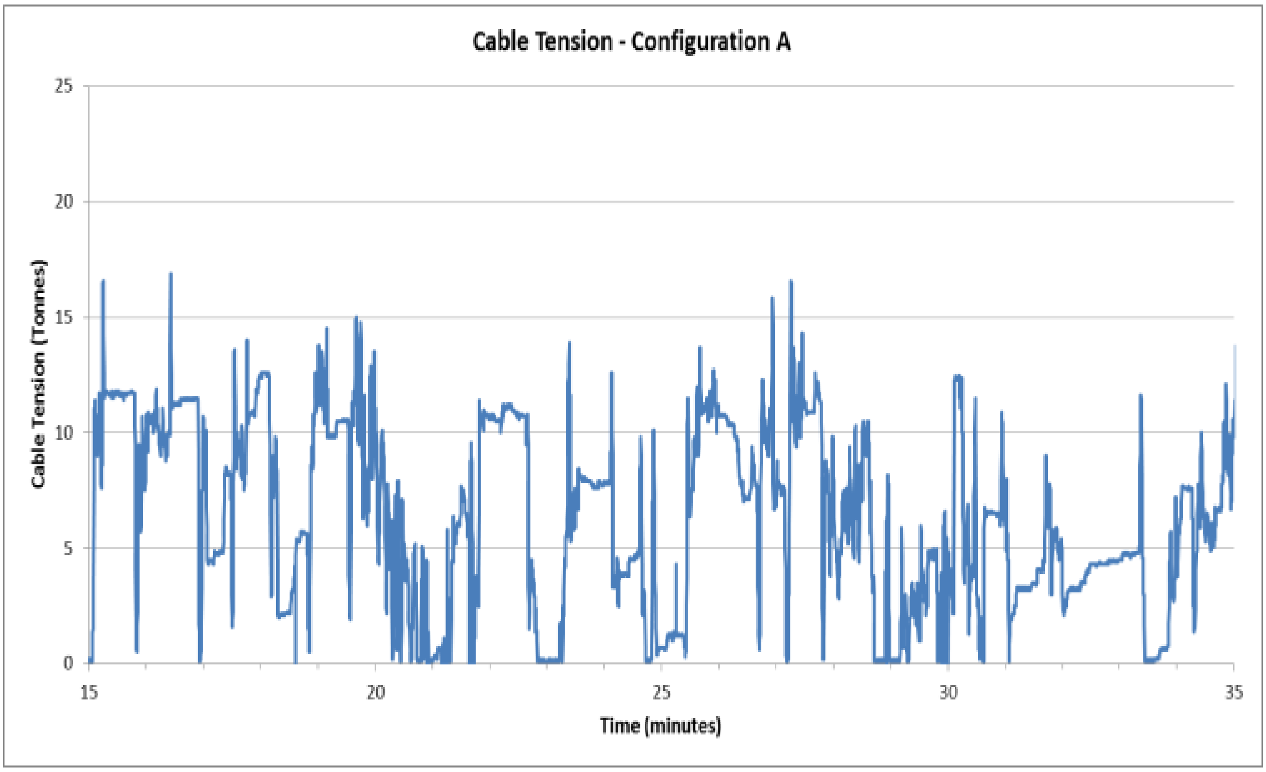


Figure 8: Configuration A - 35 minute segment of tension while working.

Configuration B: With this operation there were two distinct steady-state tensions which were approximately 9 and 12 tonnes respectively, which corresponded directly to the winch power settings selected by the operator (Figure 9). The peak tensions were sharp and uniform in size, oscillating between around 4 and 19 tonnes, with occasional spikes to 20 tonnes.

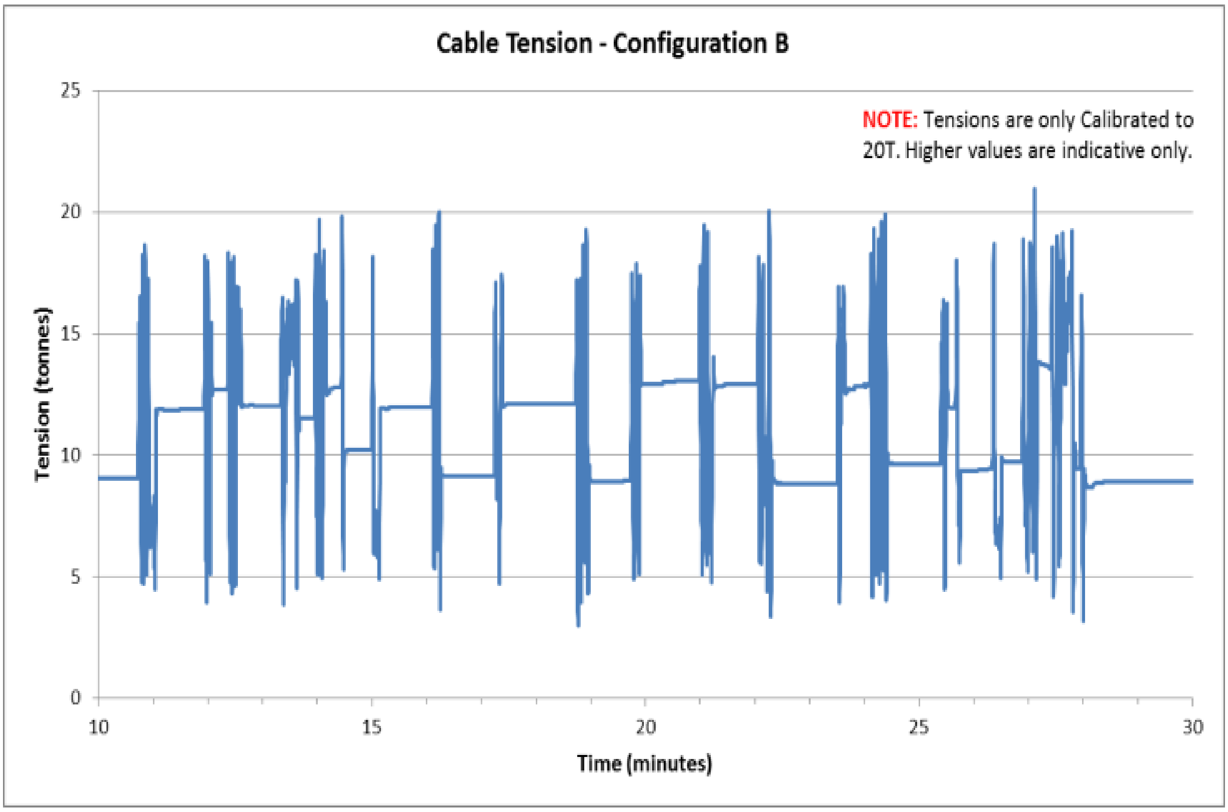


Figure 9: Configuration B - 30 minute segment of tension while working

Configuration C: The steady-state base tension for this set-up was relatively high at around 17 tonnes (Figure 10). However, the upwards tension spikes were relatively small, adding only around 3 tonnes to the base tension, resulting in spikes typically around 20 tonnes. These small amplifications of tension could be due to the dampening effect of the hydraulic ram pivoting the drum under load.

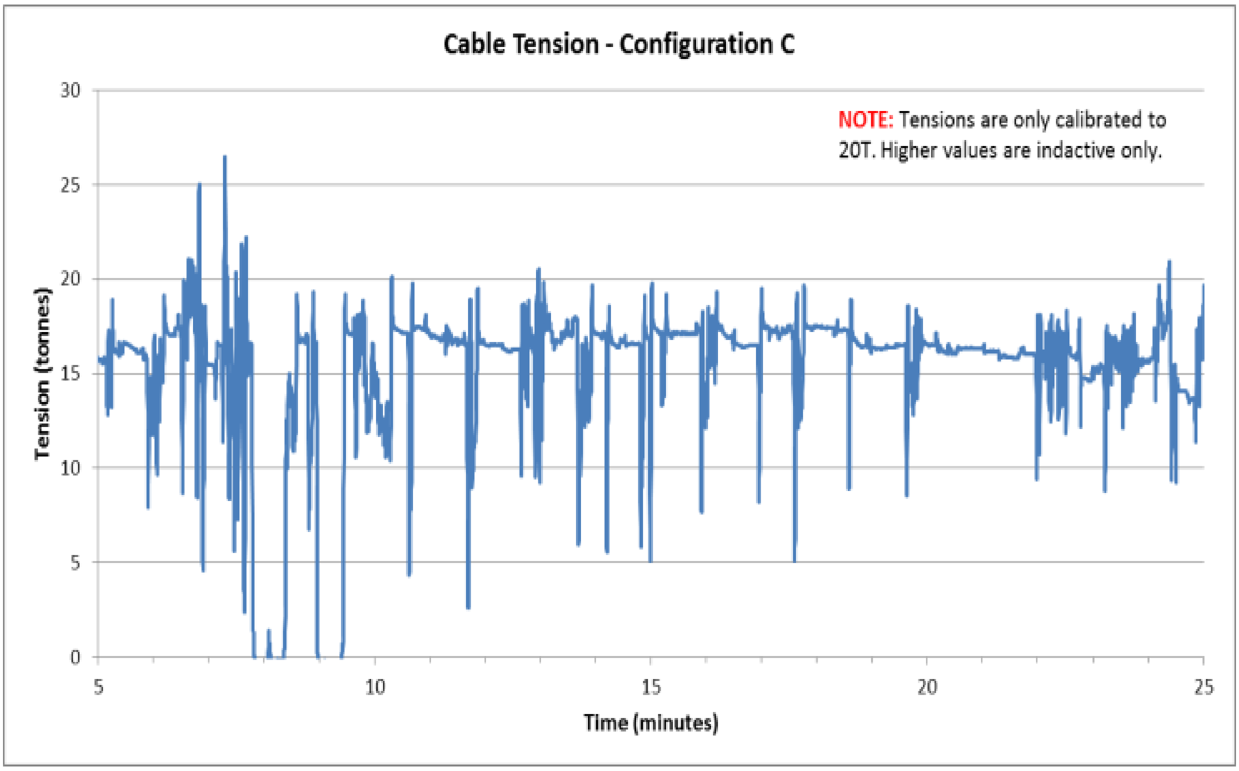


Figure 10: Configuration C - 25 minute segment of tension while working.

Tension Spikes during Movement

Results have shown that winch rope tensions while the harvester was stationary on the hillside during working phases of felling, processing, or shovelling, were relatively steady. Amplifications in tension (shock loads) occurred primarily during movement phases as the winch was required to pay out or retract the cable. Figure 11 shows the tension graph for one of the operations overlaid with a 'distance out' (red line) recording. Stationary periods related to periods of stable rope tension. This also shows that the cable tension base load was relatively low (4 to 7 tonnes) as the felling machine moved downhill and away from the winch (from 10-14 minute period). Higher base loading in the range of 9 to 12 tonnes was recorded as the felling machine was assisted back uphill towards the winch (from 14-20 minute period).

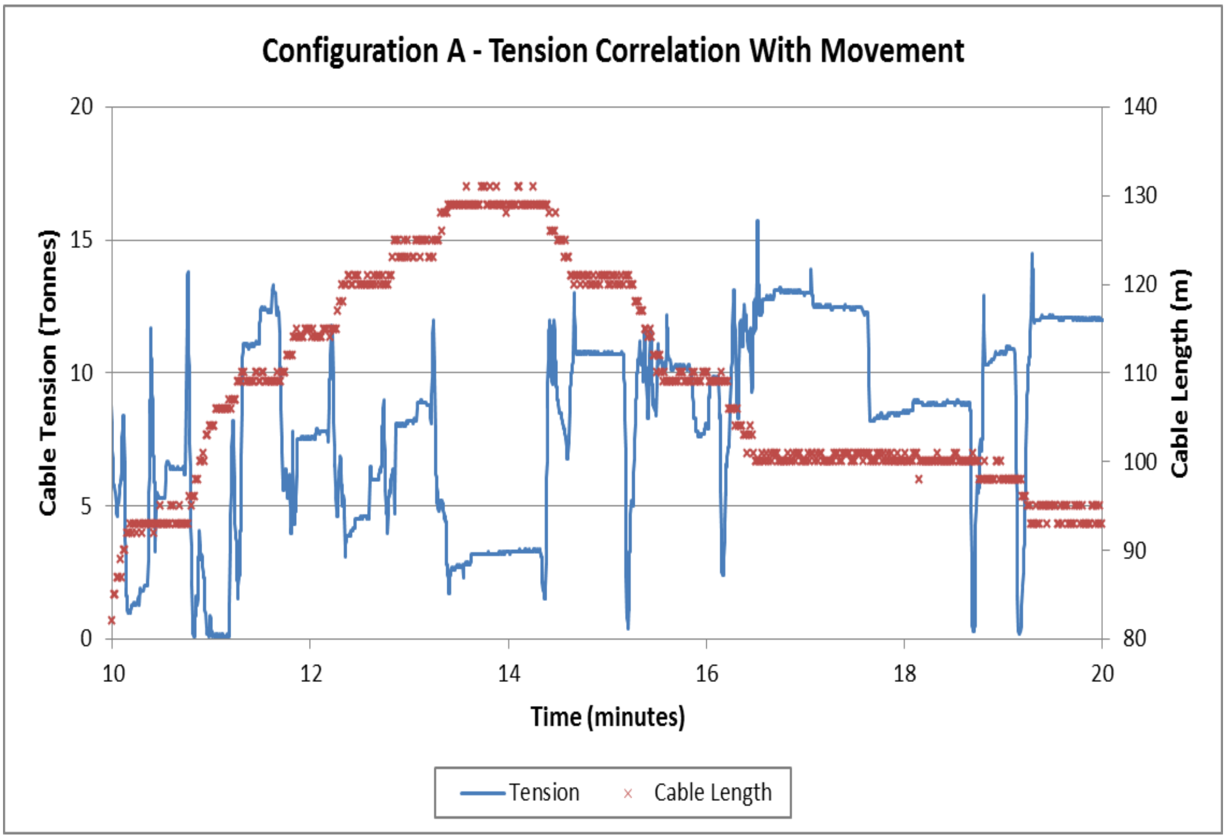


Figure 11: Tension fluctuations, with movement being indicated by a change in cable length.

Figures 12 and 13 overlay the time study results of machine movement onto the tension graph. The red line on the chart has a value of 0 when the machine was stationary, and the higher value when the machine was moving. These charts clearly demonstrate that the tension amplifications occur during the movement of the machine.

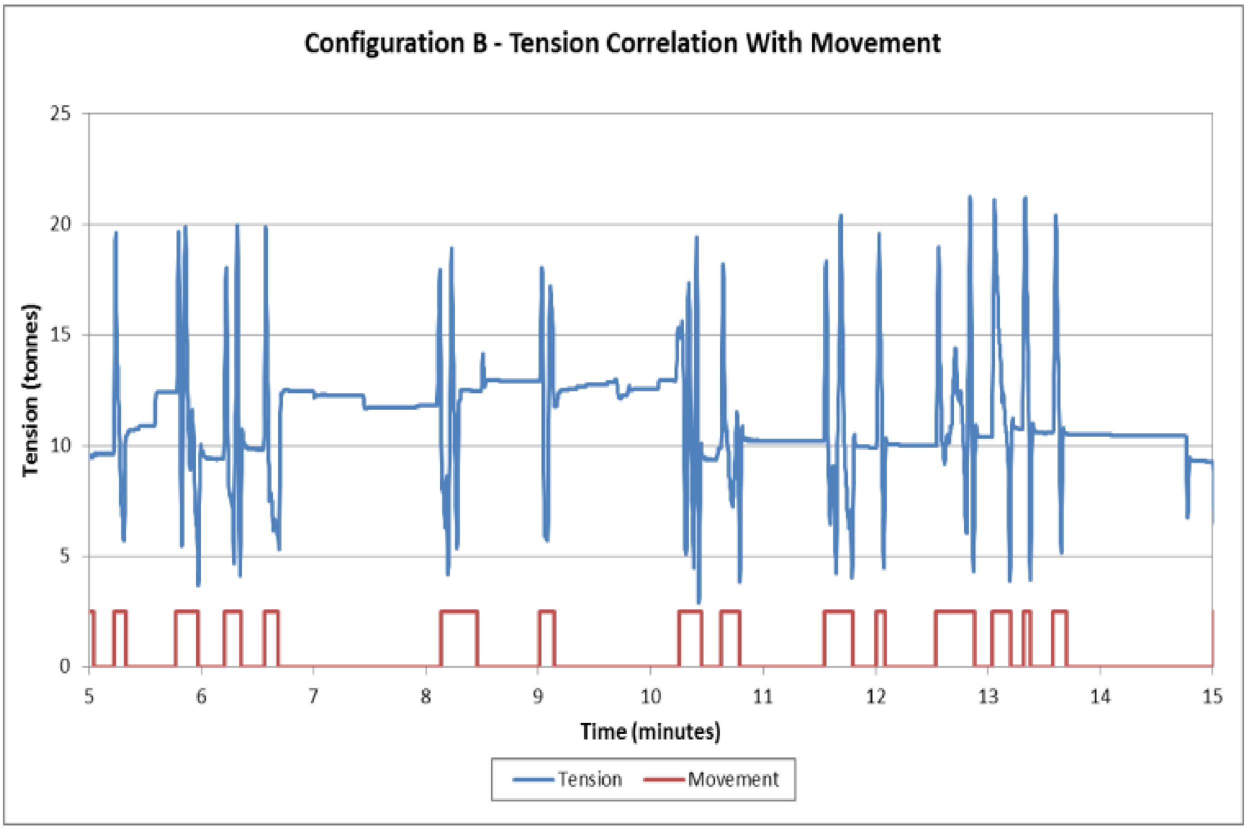


Figure 12: Tension amplifications related to machine movement (indicated by elevated red bars)

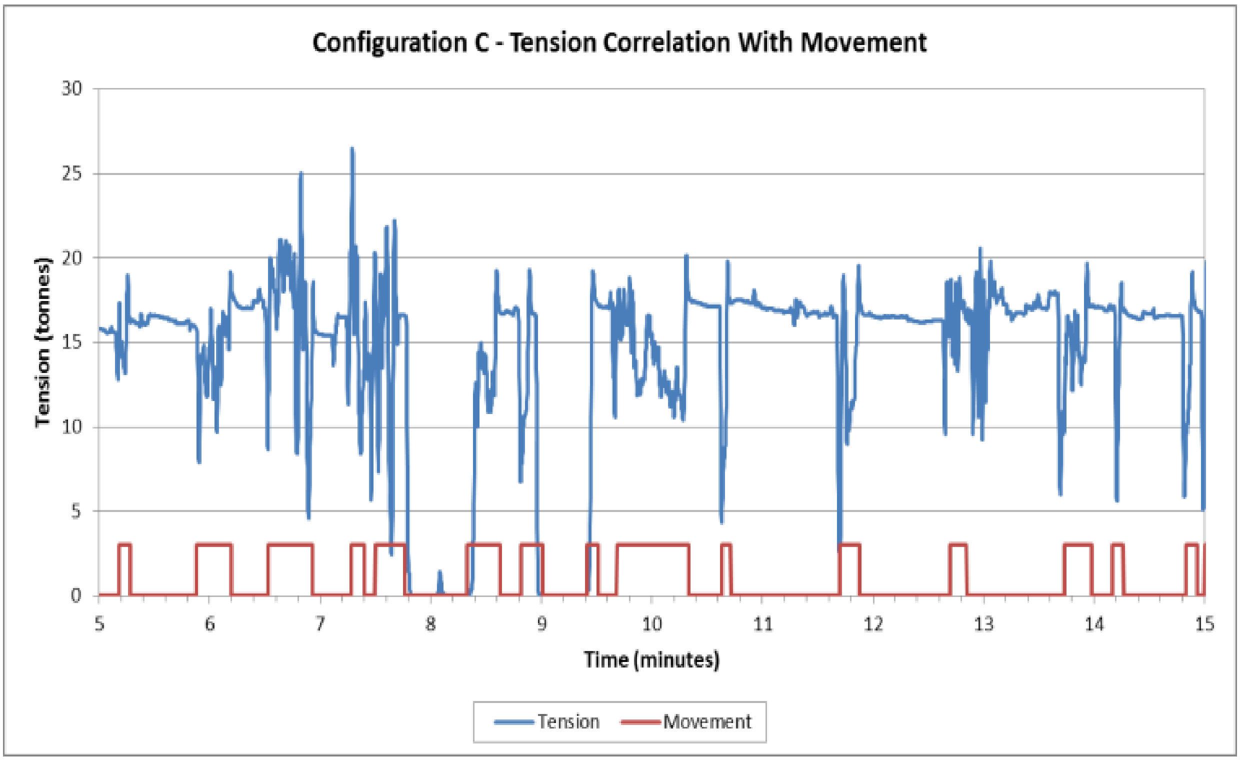


Figure 13: Tension amplifications related to machine movement (indicated by elevated red bars)

Safe Working Load Analysis

This study was mainly concerned with understanding the general behaviour of these systems. Actual tensions measured were highly dependent on machine setting (pre-set tension by operator), and also by factors such as frequency of movement.

As discussed, the safe working load (SWL) is an important design and operational factor in cable-assisted operations which is dictated by the wire rope type and dimensions, and possibly the related connections / fittings used. In New Zealand forest operations, safe working load is defined as $^{1}/_{3}$ of the wire rope's breaking strength (MBIE 2012). From previous tension monitoring of cable logging operations it is well known that most cable systems exceed SWL during shock loading as conditions of terrain and payload dictate. Systems should be designed, and planned, to operate consistently below SWL, to maximise rope life. It should be understood that only when the endurance limit of the rope is exceeded (above 50% of breaking strength) will the longevity (life) of the rope be endangered. It is also important to consider the fittings and sheaves, where rope bending stresses can add to the axial tension that is being measured and reported.

Due to the high frequency and short duration nature of the maximum tensions, four different metrics were used to gauge the system performance:

- proportion of total time that tension was above SWL;
- proportion of total time that tension was above SWL + 25% (i.e. 25% over SWL);
- frequency of tension spike events above SWL (measured in number of spikes per hour); and
- frequency of tension spike events above SWL + 25% (number of spikes per hour above 25% over SWL).

Note: SWL + 25% was chosen as a measure as it represents an overloading as per ACOP rules, but is still clearly below the endurance limit of the rope.

The results for the three configurations are presented in Table 2. Different system descriptors (X, Y and Z) are used because it is recognised that these values are operator dependant and come from a relatively small sample period, so it is not necessary to identify the actual operations. In all three operations, tensions were above SWL for only a small amount of total time. However there may have been a large number of severe shocks in that small amount of time.

Table 2: SWL performance during study

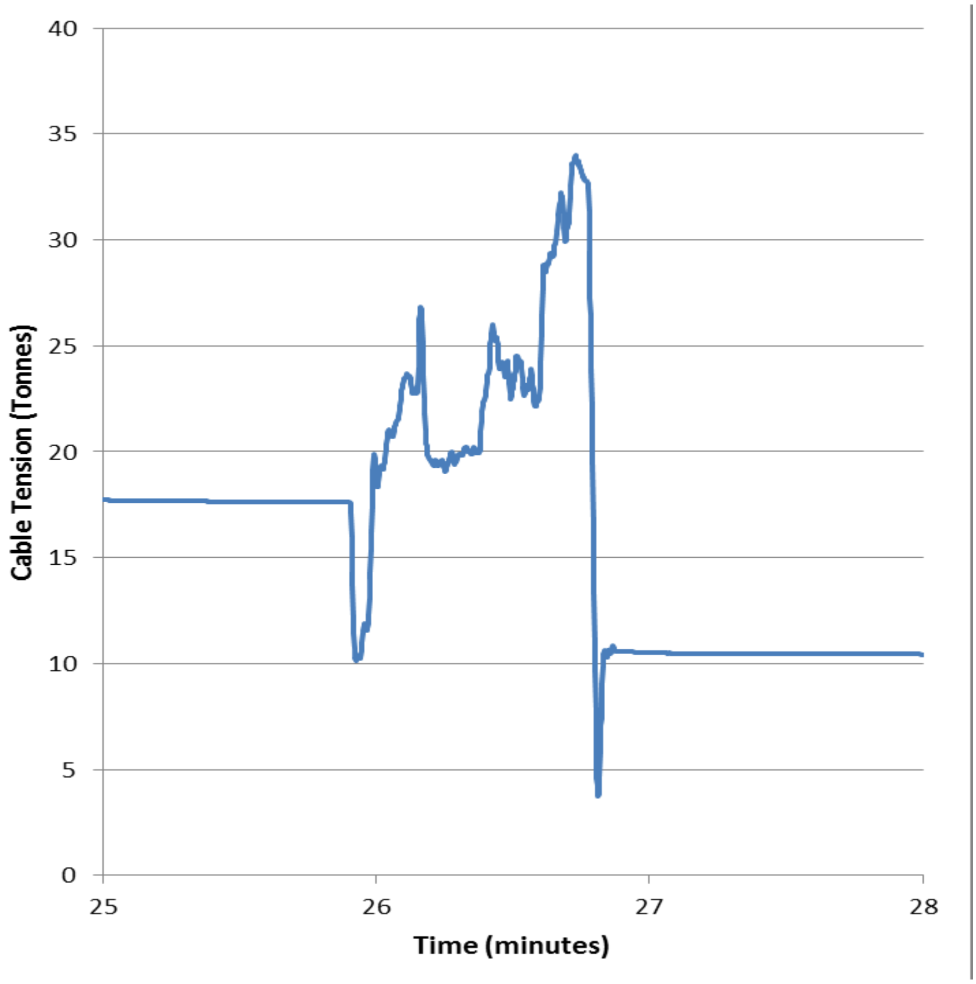
System	% time over SWL	% time over SWL+25%	Spikes over SWL per hour	Spikes over SWL+25% per hour
X	2.2	0.6	19	10
Y	0.1	0.0	3	0
Z	0.5	0.1	12	3

There were also between three and nineteen tension spikes per hour that exceeded SWL. Actual loading depended on operator setting. It is recommended that operators do not set the base tension greater than approximately 60% of SWL as shock loading during movement is likely to lift the tension up to SWL frequently.

In interpreting the results in Table 2, it could be considered that System Y had very good results where SWL was exceeded very infrequently, and tensions never exceeded 25% over SWL, so there would be little chance of rope fatigue. Conversely, System X exceeded SWL only 2.2% of total time, and results showed there were 10 spikes per hour where the peak tensions exceeded 25% over SWL. Sustained use of the cable-assisted system in this way would run a high risk of rope fatigue, shorter rope life and potentially rope damage beyond the elastic limit.

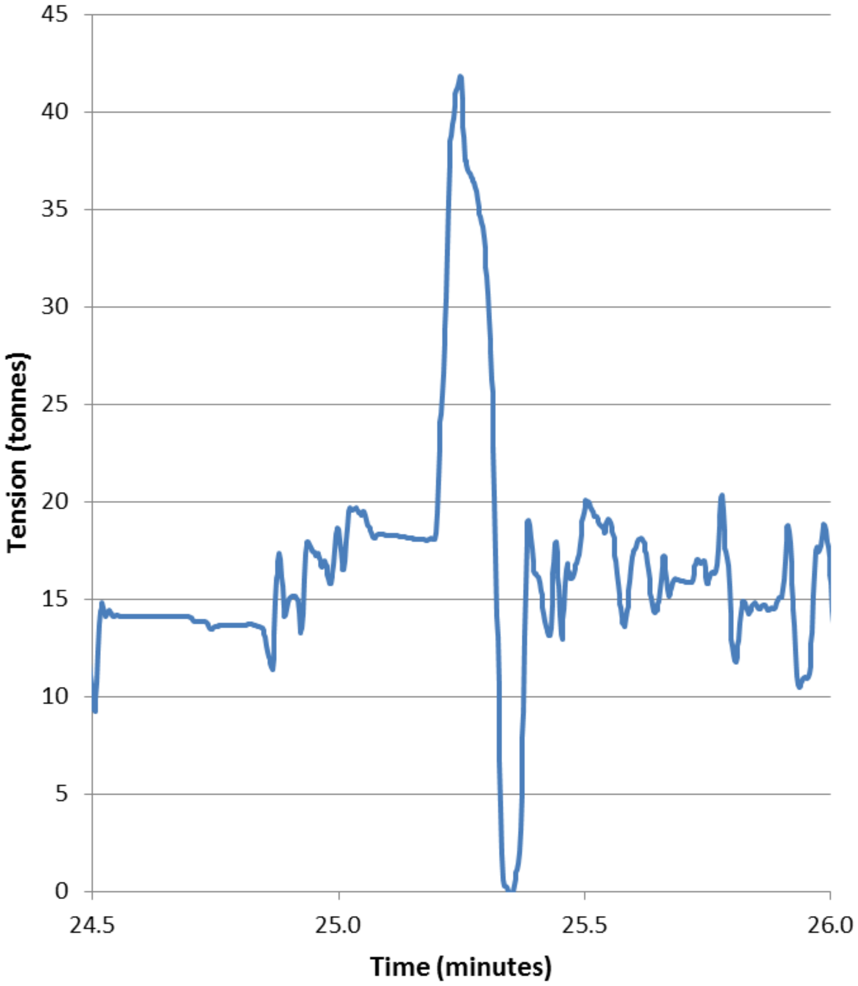
High Tension Spikes

During normal operations the tension spikes tended to be short and sharp. Despite this, they were fairly predictable in terms of both size and nature. During more 'extreme' events the tensions can reach much higher levels with far less predictability. Two examples during this study included rope tensions associated with the operator climbing out of a small 'hollow' and over an obstacle, thereby using the maximum power available in the winch-assisted machine (Figure 14).



Figures 14: Extreme tension event; negotiating an obstacle on very steep terrain.

The second example (shown in Figure 15 overleaf), can be considered as an operator error, whereby a manual setting was selected to feed out cable, but subsequently the operator did not put the system back into 'automatic' mode and hence pulled with the full force of the felling machine while moving downhill on the slope against the anchor machine. While this tension spike was attributed to operator error, it is important to learn from such mistakes, in that these machines can develop significant forces through both gravity and traction (consistent with the calculations presented by Visser 2013).



Figures 15: Extreme tension event; operator failing to engage winch correctly.

When reviewing the results of both the shock loading, and the extreme loading events that occurred during the study, there is a strong case for operators of cable-assisted systems to implement continuous tension monitoring, including the capture of the data for subsequent review.

RECOMMENDATIONS

As a result of this study, it is recommended that contractors in the New Zealand logging industry operating cable-assisted systems:

- manage wire rope tensions so that tensions do not exceed 33% of the breaking load of the wire rope;
- set the base tension less than approximately 60% of SWL as shock loading during movement is likely to lift the tension up to SWL frequently;
- review winch rope tensions regularly, especially when moving the machine; and
- give serious consideration to incorporating continuous tension monitoring and recording technology that will allow them to review and act upon operational data.

CONCLUSIONS

This study measured winch rope tensions on three different cable-assisted felling machines to provide an understanding of tension behaviour of the winch ropes during normal clearfelling operations in New Zealand. Tension monitoring results were similar across machine types and were very predictable. All shock loading occurred during machine movement and all machines exceeded safe working load (SWL) at some point during normal operation. The three operations differed by maximum tensions, cycle element, average cycle tensions, base tensions and dynamic behaviour (how tensions changed over time).

While all systems measured exceeded SWL for a small percentage of the time, two also exceeded 25% over SWL - a metric used to indicate loading at a level where it affects the longevity of the rope. There were also between three and nineteen tension spikes per hour that exceeded SWL. Actual loading depended on operator setting. Recommendations are made that operators set the base tension less than approximately 60% of SWL, as shock loading during movement may exceed SWL frequently. The uncertainty around the level of these tension spikes can be overcome by recording accurate tension data during operations.

Capturing tension data at a high frequency provides very detailed information. A ‘safety factor’ of three is used for systems where forces are not known exactly. As such it is recommended that consideration be given towards managing safe work practices that include recording tension data to establish actual tension behaviour patterns as presented in this report. It is recommended that all cable-assisted felling machines should employ a tension monitoring system of the operating rope(s) and that these tensions be recorded. Tension monitoring provides operators the assurance that they are not overloading the wire ropes; if data logged, these tensions can be recalled and evaluated to help operators learn new techniques and document wire rope wear.

Other technologies could be used in conjunction with cable-assisted machines to realise the productivity gains that these machines can have on subsequent phases such as yarding (extraction). For example, Visser *et al*. (2014) suggested that if GPS positional data and payload analysis information was overlaid and displayed to the operator (such as available from the HarvestNav App), improvements could be made to the bunching of trees to optimise payload capability of the terrain and cable logging system employed for extraction (tower height, carriage used etc.). This would enable further improvements in the productivity of the feller buncher-cable yarder system.

The information gathered during this project has been presented to all the New Zealand machinery manufacturers and they are using it to improve machine design. The information in this report has also been made available to the New Zealand forest industry as workshop material for the operator workshops run by University of Canterbury as part of this project. To date (April 2016) nine workshops have been held and there have been over 160 industry participants. This information provides a stronger knowledge basis for the next review of the Approved Code of Practice for Safety and Health in Forest Operations (ACOP).

ACKNOWLEDGEMENTS

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