COMPUTER SIMULATION OF RECOVERY ASSIST CONSTANT TENSION CABLE SYSTEM FOR HELICOPTER LANDING ON COMBATSHIP

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Abstract

This paper presents a model of a secondary unit control system for improving the dynamic performance of recovery assist (RA) cable system as used with the operation of landing a helicopter aboard ships while underway in severe sea conditions.

The control scheme features two independent adaptive controllers for serving two pressures coupled units - a primary pump unit and a secondary motor unit. The primary unit regulates the pump delivery to maintain a constant hydraulic pressure drop over the motor so that the RA cable system can be independently controlled by the secondary unit with cable tension, velocity and acceleration feedback. The model is developed from basic hydraulic equations and Newton's law. ACSL (Advanced Continuous Simulation Language) is used as the simulation environment. The effectiveness and robustness of the new control scheme of the RA cable system is examined by comparing the results of the computer simulation against applicable specifications. The results demonstrate that the new control scheme enhances the performance of the RA cable system by maintaining the cable tension within acceptable limits in spite of the continuous variation in the separation between the helicopter and the ship due to the sea conditions.

Keywords: Dynamic simulation, Load matching hydrostatic system, Secondary control unit, Helicopter landing assistance, ACSL.

1 Introduction

Landing a helicopter on the moving deck of combat ship in high seas is a difficult operation and requires special assistance equipment. The helicopter Recovery Assist, Secure and Traverse (RAST) system features a constant tension recovery assist (RA) cable which mechanically connects the helicopter to the ship, see Figure 1. The cable tension, which is generated by a hydraulically driven RA winch, is designated to act as a positional feedback to the helicopter control system as well as to the pilot, allowing him to maintain a centering position of the helicopter during hover and landing. However, the cable tension is not sufficient to haul down the helicopter. In fact, the effect of the tension does not exceed 10% of the pilot control authority. While the helicopter is in a “high hover” position (see Figure 2), which is 5~7m above the flight deck, the recovery assist (RA) cable is first attached to the helicopter's small diameter messenger cable by deck crew. Then the RA cable is reeled in and locked into the helicopter's securing probe and the RA winch is activated to apply a low-level tension. During this sequence, the pilot holds the helicopter over the mean position of the landing area.

The RA system assists the helicopter to land within the designated capture zone on the flight deck of the ship. It provides the centering action, which acts as a cue to both the pilot and the helicopter’s stability and control system. The effect of the cable tension acting on the probe is shown pictorially in Figure 3. The RA cable does not overpower the rotor thrust, but provides an upsetting cue due to the offset of the probe from the CG. This elicits a restoring control motion, in which the natural response of the avionics and the pilot to the RA cable tension makes the helicopter become centered with respect to the flight deck. The principal disturbing influence at this stage is the air wake from the hangar. With the helicopter keeping station, the RA tension is increased and the pilot descends to low hover, which is about 3m above the deck. When a quiescent period of the ship motion is identified, the pilot lands the helicopter with the aid of increased RA cable tension. The recovery process may be aborted safely at any time and the helicopter waves off to high hover while still connected to the RA cable if an emergency or sudden change in conditions should occur. When necessary, the pilot may also release the

RA cable from the probe. After touchdown, the securing device captures the helicopter's probe and the helicopter is secured to the ship.

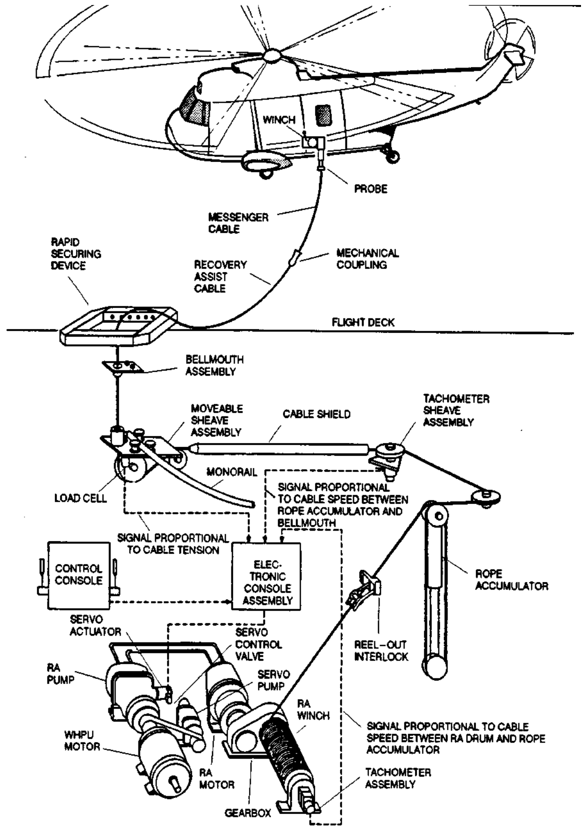

Figure 1 Diagram of helicopter Recovery Assist, Secure and Traverse (RAST) system.

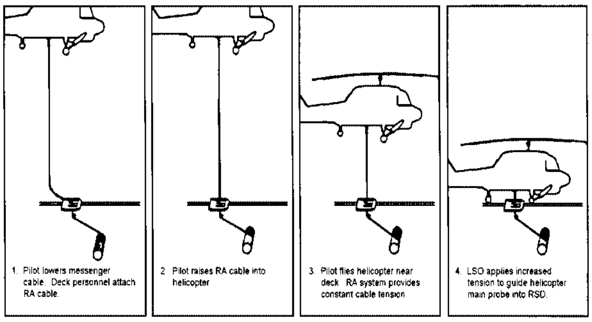

Figure 2 Different stages of assisted landing of a helicopter on ship.

Pilots experienced with the RAST operation, especially in high sea and wind conditions, claim that their workloads with cable assisted landing are significantly less than free deck landing. In an attempt to understand the effect of the cable tension during hover and landing, a model of a helicopter and a constant tension cable is used to simulate helicopter landing under various conditions of ship motion, wind and turbulence over the deck. The pilot input was limited to a step reduction in the collective sufficient to land the helicopter with acceptable landing speed. One hundred landing simulations were performed for each set of the following conditions:

- No ship motion, no wind or turbulence without cable tension,
- No ship motion, steady wind, no turbulence and without cable tension,
- Ship motion during a quiescent period, no wind, no turbulence and without cable tension,
- No ship motion, steady wind, typical turbulence due to hangar and without cable tension,
- Ship motion during a quiescent period, steady wind, typical turbulence due to hangar and without cable tension,
- Ship motion during a quiescent period, steady wind, typical turbulence due to hangar and with cable tension

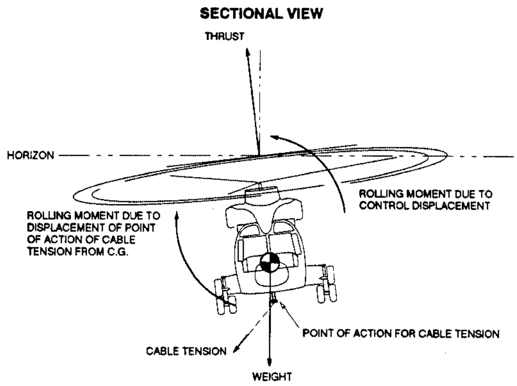

Figure 3 Illustration of cable tension effect on the helicopter.

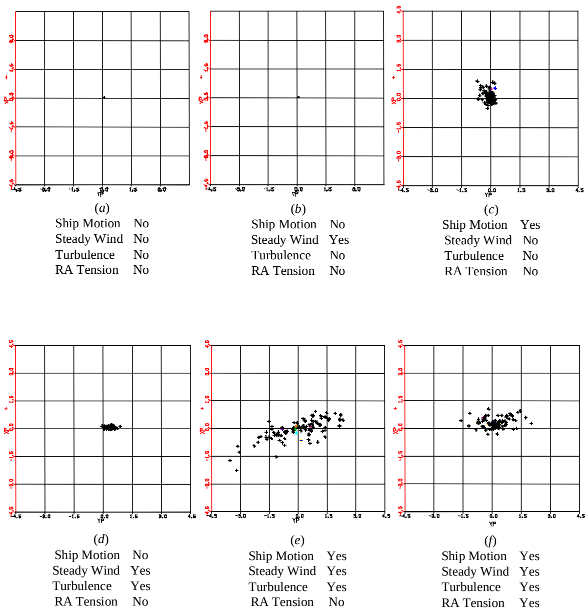

Figure 4 Landing dispersion around designated landing area under different conditions.

Figure 4 shows six plots representing the landing dispersion from mean position of landing area resulting from 100 simulation runs under each set of conditions. The first five plots shows the effect of the ship motion, the wind and turbulence in increasing the landing dispersion and consequently the pilot workload which would be required to land within limited area to allow safe securing of the helicopter. The last plot clearly shows the effect of the RA cable tension in reducing the landing dispersion and consequently the pilot workload.

Although the RA cable tension is set by the operator to a constant value, the actual tension fluctuates due to the relative motion between the ship and the helicopter, the inertia of the winch moving elements and the delays in the hydraulic system. For safe operation of the helicopter during hover and landing, the fluctuation in the cable tension must be limited such that the pilot control authority is not reduced beyond the allowed 10% [1].

The control philosophy for the RAST constant cable tension is to actively compensate for the relative motion between the ship and the helicopter by reeling in or paying out cable, depending on the tension deviation from its set value. The current RAST control system is a conventional closed flow loop hydrostatic drive, which adjusts the displacement of the pump based on cable tension and velocity feedback. The output of the motor depends on the volumetric flow and the pressure drop over the motor. However, the delay of the hydromechanical feedback [2] of such a system would not maintain the tension within the desired limits and therefore a resilient flexible spring component - the “rope accumulator” - is installed between the winch and the helicopter.

The rope accumulator is a large and complex element of the system because of the wide range requirements of the tension. Although such a system meets the operational requirements, its size and weight may not be suitable for installation on small ships. This has motivated current investigation into a more responsive control scheme, which would reduce the size of the drive system and not require a rope accumulator.

In this paper, a secondary unit control scheme [3] is adopted to achieve the required dynamic performance of the RA cable system without the need for a rope accumulator. In the new control scheme, the variable displacement pump (the primary unit) is independently controlled to provide a volumetric flow of constant pressure to the secondary unit. The RA cable winch is driven by the secondary unit, which is controlled independently by tension, velocity and acceleration feedback. The two units are connected in a pressure-coupled mode. The new system with the secondary unit control scheme has high responsiveness while maintaining good stability. The effectiveness of the new control scheme is examined by computer simulation.

The computer simulation model has been developed by utilising Advanced Continuous Simulation Language (ACSL) software [4] rather than general purpose programming languages such as FORTRAN and C++. The sophisticated user interface provided by ACSL allows one to concentrate on modeling the physical characteristics of the system while utilising the capabilities of the ACSL such as the numerical integrator, graphic data plotter, parameter entry/examination, and interactive control facilities. As a result, the model development and expansion have been relatively rapid with reduced costs and improved responsiveness to the engineering analysis and investigation needs.

This paper is divided into four sections. Following the Introduction, Section 2 describes the principles, the hydrodynamics and control laws of a secondary controlled winch drive of the proposed control scheme. Section 3 presents the implementation of the mathematical model, simulation runs of the system under the dynamics of helicopter recovery and the results of the simulation. Finally, the conclusion of the analysis is presented in Section 4.

2 Mathematical Modeling

The Electro-hydraulic secondary control system under investigation is shown in Figure 5. It consists of two subsystems, i.e., the primary and secondary units. The primary unit, which is a pressure compensated pump, delivers a volumetric flow of constant pressure to the secondary unit. The secondary unit drives a winch through a variable displacement motor that is independently controlled.

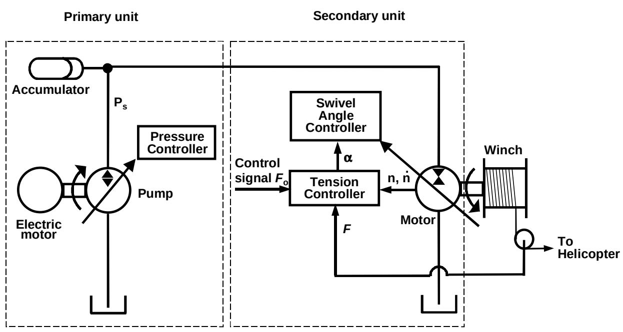

Figure 5 Block diagram of proposed RA cable system.

2.1 Primary Unit

The primary unit consists of a variable displacement pump, a pressure control valve, a hydraulic cylinder, a hydraulic accumulator and an electric motor as shown in Figure 6. The pump, driven by the electric motor, delivers volumetric flow to the hydraulic circuit. The output of the volumetric flow is controlled by adjusting the swash-plate of the pump, which is regulated by the pressure control valve and the hydraulic cylinder. The swash-plate position is adjusted due to the difference between the pre-set and current hydraulic pressure values. Thus, the primary unit is coupled with the rest of the hydraulic circuit by the hydraulic pressure.

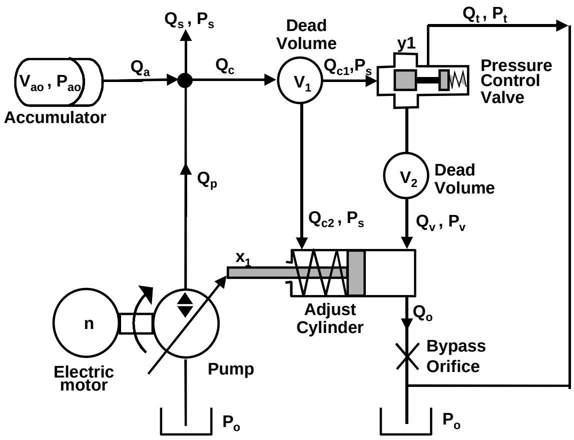

Figure 6 Control block diagram of primary unit.

From basic fluid equation [5] and Newton's law, the principal equations of the hydrodynamic model for the primary unit are established as follows:

Pump flow:

$$Q_p = \eta_v \, n \frac{x_1}{x_{1\max}} V_0 \quad (1)$$

Motion of adjust cylinder:

$$m_{c1}\,\ddot{x}_1 + c_{c1}\,\dot{x}_1 + \mu_1 \frac{\dot{x}_1}{|\dot{x}_1|} + k_{c1}\,x_1 = A_s\,p_s - A_v\,p_v - d_s\,p_s + f_{c0} \quad (2)$$

$$Q_{c2} = A_b\,\dot{x}_1 + \frac{\dot{p}_s}{E}(V_0 + A_b\,x_1) + k_l(p_s - p_a) \quad (3)$$

Pressure built up in the right chamber of adjust cylinder:

$$p_v = \frac{E}{V_2 - A_v x_1}\int [Q_v - Q_0 + A_v \dot{x}_1 - \zeta_l(p_v - p_s)]dt \quad (4)$$

Motion of pressure valve:

$$m_{v1}\,\ddot{y}_1 + c_{v1}\,\dot{y}_1 + k_{v1}\,y_1 = A_v p_s - \frac{Q_v^2\,\rho\cos 69^0}{(y_1 - R)\sqrt{2Ry_1 - y_1^2} + R^2\cos^{-1}(1 - y_1/R)} - f_{v0} \quad (5)$$

Pressure valve flow:

$$Q_v = \begin{cases} Q_{c1} = q_0\sqrt{\dfrac{2}{\rho}(p_s - p_v)} & y_1 \ge y_0 \\ Q_t = q_0\sqrt{\dfrac{2}{\rho}(p_v - p_0)} & y_1 < y_0 \end{cases} \quad (6)$$

where

$$q_0 = 0.7\left[(y_1 - R)\sqrt{2Ry_1 - y_1^2} + R^2\cos^{-1}\left(1 - \frac{y_1}{R}\right)\right]$$

Orifice flow:

$$Q_0 = \begin{cases} 0.7A_0\sqrt{\dfrac{2}{\rho}(p_v - p_0)} & p_v \ge p_0 \\ 0 & p_v < p_0 \end{cases} \quad (7)$$

System pressure with hydraulic accumulator:

$$p_s = \begin{cases} \dfrac{E}{V_1}\displaystyle\int (Q_p - Q_c - Q_s - Q_{leak})dt & p_s > p_{ao} \\ \dfrac{1}{C}\displaystyle\int (Q_p - Q_c - Q_s - Q_{leak})dt & p_s \le p_{ao} \end{cases} \quad (8)$$

where

$$C = \frac{V_1 + V_{ao}\left[1 - \left(p_{ao}/p_s\right)^{1/\chi}\right]}{E} + \frac{V_{ao}\left(p_{ao}/p_s\right)^{1/\chi}}{p_s\chi}$$

2.2 Secondary Unit

The secondary unit is composed of a variable displacement motor, a winch drum connected to the motor through a gearbox, a hydraulic cylinder that adjusts the motor swash-plate position, a servo-valve that controls the cylinder and an electronic controllers for the servo-valve. The control system consists of five control loops. They are: 1) cable tension forward control, 2) cable tension PI feedback control, 3) motor speed feedforward control, 4) motor acceleration feedforward control and, 5) motor swash-plate position feedback control.

The cable tension forward control applies the required cable tension while the cable tension feedback control helps to prevent cable tension drifting from its pre-set value. The feedforward controls of speed and acceleration of the motor are aimed to compensate for the effect of the motor friction and inertia and to improve the responsiveness of the secondary unit. However, this type of feedforward control must be carefully adjusted as it may cause instability of the secondary unit.

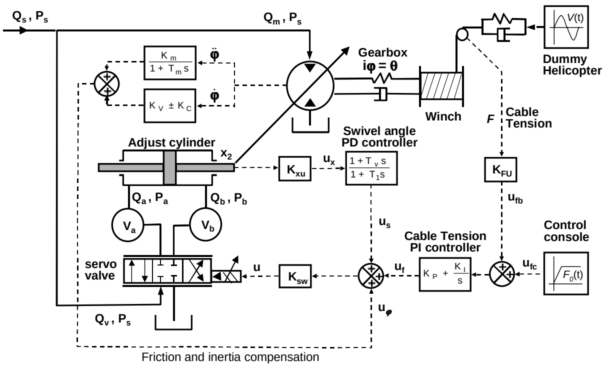

Figure 7 Control block diagram of secondary unit.

Figure 7 shows the hydraulic circuit and the control loops of the secondary unit. It can be seen that the motor is controlled independently by the volumetric flow, which is regulated by the cable tension feedback, since the hydraulic pressure is maintained constant by the primary unit. A hydrodynamic model is developed based on the block diagram shown in Figure 7. The principal equations of the system are established by the basic fluid mechanics equation [5] and Newton's law as follows:

Motion of adjust cylinder:

$$m_{c2}\,\ddot{x}_2 + c_{c2}\,\dot{x}_2 + \mu_2 \frac{\dot{x}_2}{|\,\dot{x}_2\,|} = A\,(p_a - p_b) - f_g \tag{9}$$

Motion of servo-valve:

$$\ddot{y}_2 + 2\xi_2\omega\,\dot{y}_2 + \omega^2\,y_2 = \omega^2\,\frac{u_v}{u_n} \tag{10}$$

Servo-valve flow:

$$\left.\begin{aligned} & y2 \;>\; 0 \\ & \quad Q_a = y_2\,Q_n\,\mathrm{sign}(p_s - p_a)\sqrt{\frac{|\,p_s - p_a\,|}{0.5\,p_n}} \\ & \quad Q_b = y_2\,Q_n\,\mathrm{sign}(p_a - p_0)\sqrt{\frac{|\,p_a - p_0\,|}{0.5\,p_n}} \end{aligned}\right\} \tag{11a}$$

$$\left.\begin{aligned} & y2 \;<\; 0 \\ & \quad Q_a = y_2\,Q_n\,\mathrm{sign}(p_a - p_0)\sqrt{\frac{|\,p_a - p_0\,|}{0.5\,p_n}} \\ & \quad Q_b = y_2\,Q_n\,\mathrm{sign}(p_s - p_b)\sqrt{\frac{|\,p_s - p_b\,|}{0.5\,p_n}} \end{aligned}\right\} \tag{11b}$$

Pressure built up in chamber A and B of adjust cylinder:

$$\left.\begin{aligned} p_a &= \frac{E}{V_a + A\,x_2}\int [Q_a - A\,\dot{x}_2 - \zeta_2(p_a - p_b)]\,dt \\ p_b &= \frac{E}{V_b - A\,x_2}\int [A\,\dot{x}_2 + \zeta_2(p_a - p_b) - Q_b]\,dt \end{aligned}\right\} \tag{12}$$

Motion of hydraulic motor:

$$I_m\ddot{\varphi} + c_m\dot{\varphi} + M_m\frac{\dot{\varphi}}{|\,\dot{\varphi}\,|} = \frac{V_\varphi}{2\pi}\frac{x_2}{x_{2\,\max}}(p_s - p_o) - M_g \tag{13}$$

Motor flow:

$$Q_m = \frac{V_\varphi}{2\pi}\frac{x_2}{x_{2\,\max}}\dot{\varphi} \tag{14}$$

Gearbox without backlash:

$$M_g = k_g\left(\frac{\varphi}{i} - \theta\right) + c_g\left(\frac{\dot{\varphi}}{i} - \dot{\theta}\right) \tag{15}$$

Motion of winch:

$$I_w\,\ddot{\theta} + c_w\,\dot{\theta} + M_w\frac{\dot{\theta}}{|\,\dot{\theta}\,|} = iM_g - F\,R_w \tag{16}$$

Cable tension:

$$F = k_f\,\Delta L + c_f\,\frac{d}{dt}(\Delta L) \tag{17}$$

3 Simulated Performance

The dynamic model of the proposed RA cable system is implemented utilising ACSL software simulation package. The dynamic characteristics of the proposed control scheme were evaluated by running the simulation and analysing the system response for various tension demands. The system responses are also compared to the required performance according to the operational specifications of the system as stated in MIL-R-85111A. [1].

3.1 Simulation of Constant Cable Tension Control for Helicopter Hovering

The performance specification of the RA system was established based on the operational requirement for recovering a helicopter under Sea State 5, North Atlantic sea and wind conditions. Under these conditions, the deck could be heaving with maximum speed of 18 feet per second relative to the helicopter. As mentioned before, it is essential to limit the tension deviation from the pre-set value to ensure safe recovery of the helicopter under such severe conditions. The cable tension deviations from the mean value, when the cable speed is changing with sinusoidal cycles of 9.5 cycles per minute shall not exceed the allowable limits stated in Mil-R-85111A.

Nominal Mean Cable Tension (lbs)	Peak Cable Speed (ft/sec)	Tension Deviation Limit (±lbs)	Simulated Tension Deviation (±lbs)
850	18	225	108
1500	18	225	108
2000	18	300	108
3000	13.3	400	114
3500	11.4	400	119
4000	10	400	122

Table 1 Comparison of simulated and allowed cable tension deviations for different nominal

Table 1 summarises the simulation results and comparison with the Mil-R-85111A specification for different combinations of cable tension and speed. A sample of the simulation results of the cable tension, cable speed and the volumetric flow of the pump and motor are shown in Figure 8. The shown case represents that of 850 pounds nominal mean tension with peak cable speed of 18 feet per second. It can be seen that the RA cable system with the proposed control scheme meets the required system specifications. The winch paid out and reeled in the RA cable with almost the same speed as the input cable speed. The maximum tension deviation (peak to peak) was much less than the allowed value. The tension spikes appear at the zero crossing point of the cable speed are caused by the friction model in the RA cable system. In reality, the tension spikes due to the frictional forces are much less severe than in simulations as the real frictional forces change continuously across zero speed point. Due to simplification in the friction model, there is discontinuity in the frictional force at the zero speed crossing point. It is predicted that the spikes in actual system would be much less. If the tension spikes due to the frictions are discarded, the tension deviations are about 5% of the nominal mean values.

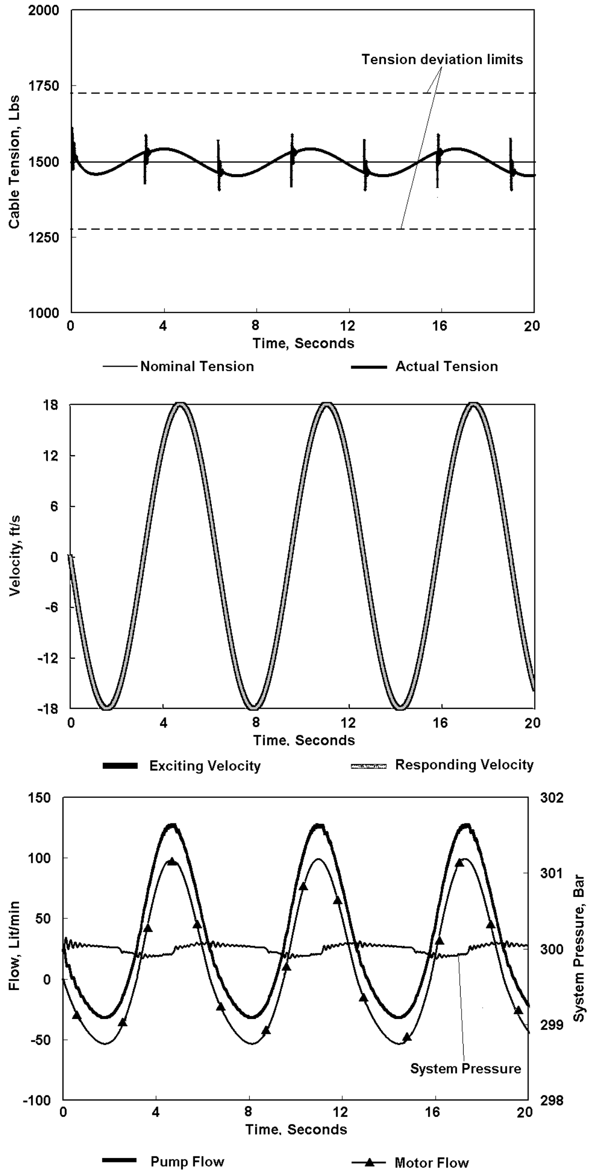

Figure 8 Simulation results of constant cable tension control. Nominal cable tension: 850 lbs. Peak cable speed: 18 ft/sec.

Figure 8 also show that the primary unit effectively maintained a constant pressure although the volumetric flows of the motor and pump changed in a similar sinusoidal manner of the cable speed. In the reversed cycle, the motor worked as a pump and the pump worked as a motor. Part of the energy can be recovered by storing the high-pressure flow into a hydraulic accumulator.

3.2 Simulation of Helicopter Landing Bounce

The transient effect of the helicopter landing bounce can generate an enormous tension spike, which may cause breaking the safety pin in the RA cable attachment. To eliminate the possibility of high-tension spikes at landing, it is essential that the RA system be able to respond to the sudden increase in cable tension. The safety pin is designed to break at 6000 pounds and according to Mil-R-85111A [1], the peak cable tension should not exceed 5500 pounds when the cable is stopped from a speed of 12 ft/sec to zero with pre-set cable tension of 4000 pounds. In the simulation, the landing bounce was modelled by reducing cable peak speed of 12 ft/sec to zero within 0.2 second while the nominal cable tension is set at 4000 pounds. Figure 9 shows the landing bounce simulation results. It can be seen that the overshoot of cable tension due to the fast stopping of the cable motion was 4460 pounds, which is much less than the allowed value of 5500 pounds. It can also be seen that the changes in the motor and pump flow followed closely the reduction rate in the RA cable speed. Although there is a large and rapid reduction in the volumetric flow between the pump and the motor, the change in the pressure was negligible. This demonstrates the high responsiveness of both the primary and the secondary control systems.

4 Conclusion

A computer simulation study has been undertaken to examine a new control concept for the recovery assist (RA) cable of ITI's RAST system. In the new concept, a secondary control is used where the pump and the motor are controlled separately by two independent adaptive controllers. Two major advantages of the concept have been demonstrated in this paper. Firstly is the high responsiveness of the system. Secondarily is the ability of the hydraulic system to recover energy. The high responsiveness is achieved by adopting the two independent adaptive controllers. The primary unit maintains constant pressure of the system. The secondary unit controls the hydraulic motor directly by regulating its volumetric displacement according to the tension, velocity and acceleration control feedback. Energy recovery can be realised by adding a hydraulic accumulator to the high-pressure side of the system to recover energy during the reversed cycle when the motor works as a pump. The typical recovery conditions of the helicopter have been simulated and the response of the RA cable system was found to meet the system specifications.

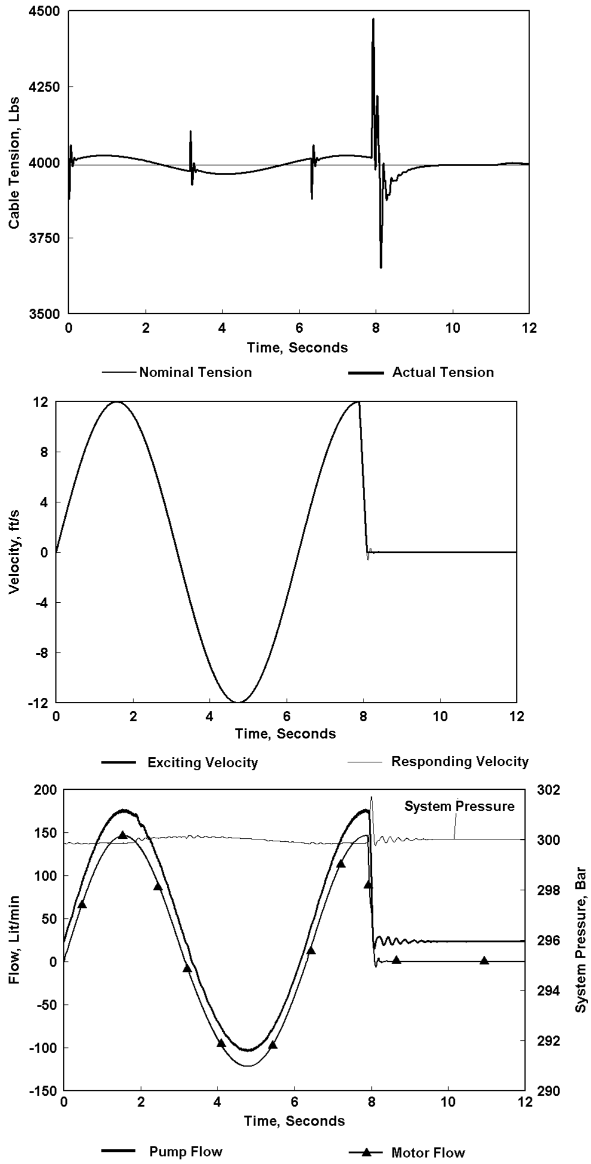

Figure 9 Simulation results of helicopter landing bounce.

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