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Published in:
Proceedings for AIAA Guidance Navigation and Control Conference

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Swing Damping for Helicopter Slung Load Systems using Delayed Feedback

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This paper presents the design and verification of a swing reducing controller for helicopter slung load systems using intentional delayed feedback. It is intended for augmenting a trajectory tracking helicopter controller and thereby improving the slung load handing capabilities for autonomous helicopters. The delayed feedback controller is added to actively reduce oscillations of the slung load by improving the damping of the slung load pendulum modes. Furthermore, it is intended for integration with a feedforward control scheme based on input shaping for concurrent avoidance and dampening of swing. The design of the delayed feedback controller is presented as an optimization problem which gives the possibility of an automated design process. Simulations and flight test verifications of the control system on two different autonomous helicopters are presented and it is shown how a significant improvement of oscillation damping can be achieved.

I. Introduction

A helicopter is a highly versatile aerial vehicle and its unique flying characteristics enables an intriguing ability to carry loads hanging in wires underneath the helicopter. Flying with an underslung load is known as either slung load or sling load flight and it is widely used for different kinds of cargo transport. However, flying a slung load can be a very challenging and sometimes hazardous task as a slung load significantly alters the flight characteristics of the helicopter. The pendulum-like behavior of the slung load gives a high risk of pilot induced oscillations that can result in dangerous situations[1]. Furthermore, unstable oscillations can occur at high speeds due to the different aerodynamic shapes of the slung loads. There is therefore, from helicopter pilots and from the aerospace industry in general, a large interest in technologies that can reduce the challenge in operating helicopter slung loads. Almost all research in this area has been focused on modeling and stability analysis[2,3]. The design of an autonomous Unmanned Aerial Vehicle (UAV) carrying slung loads is rarely seen in the literature.

The focus of this research is on enabling slung load flight in autonomous helicopters for general cargo transport. This is characterized by a suspension system that uses a single attachment point on the helicopter and by unknown slung load parameters. There is no specific tracking requirement for the slung load, but stable flight must be ensured, which is done through keeping load swing at an acceptable level. This is achieved through a three step approach: First an adaptive slung load estimator is designed using vision based sensor data that is capable of estimating the length of the suspension system together with the system states and thereby adapt the model[4]. The second step is the development of a feedforward control system based on input shaping that can be put on an existing autonomous helicopter and make it capable of performing maneuvers with a slung load without unnecessarily large oscillations[5]. The final and third step is to design a feedback control system to actively dampen oscillations of the slung load. Both the feedforward and feedback are designed to easily handle varying wire length and together with the adaptive slung load estimator they form an integrated control system as shown in figure 1.

The contribution of this paper is the development of the swing damping feedback controller using a optimized delayed feedback approach. The paper starts with a discussion of previous work followed by an

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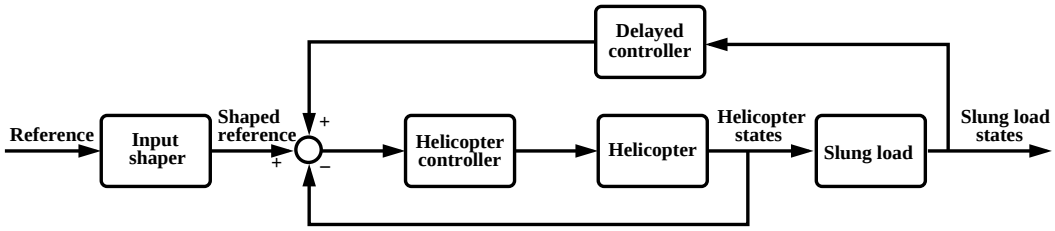

Figure 1. Architectural overview of the swing damping control scheme.

introduction to the test systems used in this paper. Then the general theory of delayed feedback is presented and following that design examples are given. Finally, the effect of the controller is illustrated both simulation and flight verification.

I.A. Previous Work

A number of different publications on feedback control of helicopter slung load systems exist, but actual flight verification is very sparse in the literature. Feedback from the load wire rates to either main rotor thrust angles or to attachment point position was analyzed by T. A. Dukes 1973 and he concluded that feedback to rotor input gives only limited performance while feedback to the attachment point position is more advantageous[6]. Furthermore, he mentioned the problem of state estimation for slung load systems[7], and to overcome this problem an open loop control approach was suggested. This open loop control method resembles input shaping in the sense that the controller is designed such that excitation of the resonant modes is avoided, in this case by using appropriate spaced triangular pulses as control input. Gypta and Bryson suggested a LQR controller for a S-61 Sikorsky helicopter for near hover stabilization with a single wire suspension[8]. SISO controllers were designed for the lateral and longitudinal axis taking wind disturbances into account. The resulting design is left untested, but stability and performance analysis shows satisfying results. An active control system mounted on the actual slung load has been proposed , which consists of two vertical aerodynamic control surfaces intended to dampen oscillation on the load yaw and lateral axis in a single wire suspension system[9]. Controller design was done using LQR and it is shown through linear analysis that the system is capable of stabilizing the system up to quite high airspeeds.

Robust control has been used for stabilization of a helicopter with a point mass slung load[10]. Controller design is done based on a reduced order linear model using $\mathcal{H}_\infty$ synthesis and it is shown through simulation to be able to stabilize the system. Receding Horizon Optimal control is suggested in [11] and preliminary simulation results is presented.

I.B. Helicopter Systems

We will here illustrate how a delayed feedback controller is use on two very different autonomous helicopter systems: The Aalborg University Corona Rapid Prototyping Platform and the Georgia Tech GT-Max.

The AAU Corona is a 1 kg electric indoor helicopter flying with a 0.15 kg slung load in a single 1.25 m wire. It performs fully autonomous flight with landings and takeoff using a set of gain-scheduled PID controllers. Helicopter and slung load state measurements are acquired using a Vicon motion tracking system.

The GT-Max of the Georgia Tech UAV Research Facility is a 100 kg helicopter with 3 m rotor diameter and is fully autonomous system using an IMU driven state estimator and an adaptive controller. The slung load is a 5.5 kg bucket suspended in a 7 m wire.

II. Delayed Feedback Control

The idea for the delayed controller is that by using intentionally delayed feedback it is possible to absorb vibrations in a oscillating system. Traditionally, delay in feedback systems is considered problematic and causes deteriorating performance and even instability, but in this approach we use the delay to our advantage.

It was first suggested in[12] which consider vibration damping in structures where it was denoted 'Delayed Resonator'. The delayed resonator is designed as an oscillator with a natural frequency equal to that of the system, and with an appropriate delay this can be fed to the system and cancel the system vibrations. In[13]

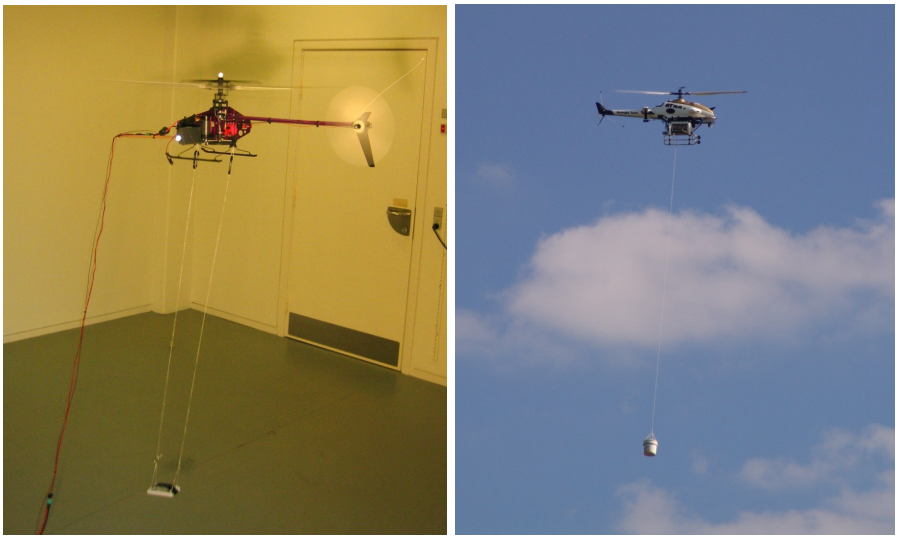

Figure 2. Left: The Aalborg University Corona flying indoor with slung load. Right: The GT-Max equipped with a single wire slung load.

the concept is extended to handle dual mode resonant systems. A comparison of the delayed resonator with a standard PD controller is made in[14] and it is concluded that a comparable performance can be achieved with the two. However, the delayed feedback has a number of advantages over the PD controller, most prominently the ability to incorporate system delays into the controller without loss of performance. This is especially true in this case where slung load measurements are provided by a vision/image processing system which on systems with low computational power can result in long delays. In[15] and[16] the delayed resonator is used to dampen swing in ship cranes. Also[17] extends the concept to consider both negative and positive feedback and applies it to vibration damping in structures.

II.A. Delayed Feedback Theory

A standard linear second order system is given by

$$\ddot{x}(t) + 2\omega_n\zeta\dot{x}(t) + \omega_n^2 x(t) = u(t)\,, \tag{1}$$

where ω_n is the natural frequency and ζ is the damping. We then use a proportional feedback of the time delayed state value

$$\ddot{x}(t) + 2\omega_n\zeta\dot{x}(t) + \omega_n^2 x(t) = G_d x(t-\tau_d)\,, \tag{2}$$

where design parameters of the controller are the gain G_d and the time delay τ_d. In the Laplace domain (2) becomes

$$x(s^2 + 2\omega_n\zeta s + \omega_n^2) = G_d e^{-\tau_d s}\,. \tag{3}$$

More or less complicated approaches have been suggested in the literature for analyzing the system and designing the controller, see e.g.[15] However, we will here propose a simple approach and model the delay using a Padé approximant. A second order Padé approximant is given by

$$e^{-\tau_d s} = \frac{1 - \tau_d/2s + \tau_d^2/12s^2}{1 + \tau_d/2s + \tau_d^2/12s^2}\,, \tag{4}$$

and by using this approximation we can simply apply known linear system theory. The delayed feedback controller can then be modeled is state space form as

$$\boldsymbol{A}_C = \begin{bmatrix} -6/\tau_d & -12/\tau_d^2 \\ 1 & 0 \end{bmatrix}, \boldsymbol{B}_C = \begin{bmatrix} G_d \\ 0 \end{bmatrix}, \boldsymbol{C}_C = \begin{bmatrix} -12G_d/\tau_d & 0 \end{bmatrix}, \boldsymbol{D}_C = 1\,.$$

II.B. Automated Design of the Delayed Feedback Controller

The purpose of the controller is to dampen the pendulous modes of the slung load within the limits of the helicopter performance. The design of the controller can then be formulated as finding the controller parameter set (G_d, τ_d) that achieves the maximum damping of the pendulous modes while maintaining satisfactory helicopter behavior.

Let the linear system

$$\boldsymbol{H} = \begin{cases} \dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \end{cases} , \tag{5}$$

where $\boldsymbol{x} \in \mathbb{R}^n$ is the state vector, $\boldsymbol{u} \in \mathbb{R}^m$ is the input vector, and $\boldsymbol{y} \in \mathbb{R}^p$ is the output vector, be the positive feedback close loop system

$$\boldsymbol{H} = \frac{\boldsymbol{P}}{1 - \boldsymbol{P}\boldsymbol{C}} \tag{6}$$

of the plant ($\boldsymbol{P}$) and the delayed feedback controller ($\boldsymbol{C}$). For this system the eigenvalues are given by

$$(\boldsymbol{A} - \boldsymbol{\lambda}\boldsymbol{I})\boldsymbol{x} = 0 , \tag{7}$$

where $\boldsymbol{\lambda} \in \mathbb{C}^n$ is the vector of eigenvalues with a corresponding vector $\boldsymbol{\zeta} \in \mathbb{R}^n$ of dampings. The damping $\zeta_i \in \boldsymbol{\zeta}$ of the i'th eigenvalue $\lambda_i \in \boldsymbol{\lambda}$ can be found as

$$\zeta_i = \frac{\mathrm{Re}(\lambda_i)}{\omega_{ni}} \tag{8}$$

with

$$\omega_{ni} = |\lambda_i| . \tag{9}$$

We then define the controller design as finding the set of control parameters that yields the maximum of the smallest eigenvalue damping

$$\underset{(G_d,\tau_d)}{\arg\max} \quad \min_i \zeta_i . \tag{10}$$

Given this formulation the process of designing the controller can be completely automated using optimizations tools.

II.C. Cart/Pendulum Example

To exemplify the controller strategy we design a delayed feedback controller to dampen oscillation in a classical cart/pendulum system. The pendulum model can be described by a linear second order system from cart acceleration to pendulum angle

$$\frac{\theta}{x} = \frac{-\frac{1}{l}s^2}{s^2 + \frac{g}{l}} . \tag{11}$$

We define the delayed feedback controller as

$$x_r(t) = G_d l \sin(\theta(t - \tau_d)) , \tag{12}$$

which is equivalent to feedback from the relative position between cart and pendulum given by $l\sin(\theta)$. This actually means that the controller gain G_d can be seen as normalized with respect to the pendulum length. Furthermore, we define the controller delay as normalized with respect to the pendulum oscillation period T_n

$$\tau_d = T_n \tau_n , \tag{13}$$

where

$$T_n = 2\pi\sqrt{\frac{l}{g}} . \tag{14}$$

Since both controller parameters are defined as normalized to the pendulum length we can design the controller for one pendulum length and when the length is changed, the controller is redesigned accordingly in a automated way. Thereby, the same oscillation damping is achieved for any pendulum length.

The control parameters are found by solving (10), which corresponds to finding the maximum in figure 3. This figure shows a map of the system most resonant pole damping as a function of controller parameters.

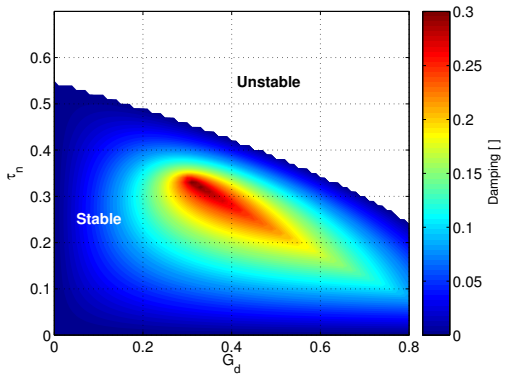

Figure 3. Cart/pendulum example. Damping of the system as a function of delayed feedback controller parameters.

The design process returns the following control parameters

$$G_d = 0.325\,, \qquad \tau_n = 0.325\,, \tag{15}$$

which results in a damping of $\zeta = 0.3$. This is illustrated in figure 4 where it can be seen that the feedback law dampens the pendulum swing very quickly.

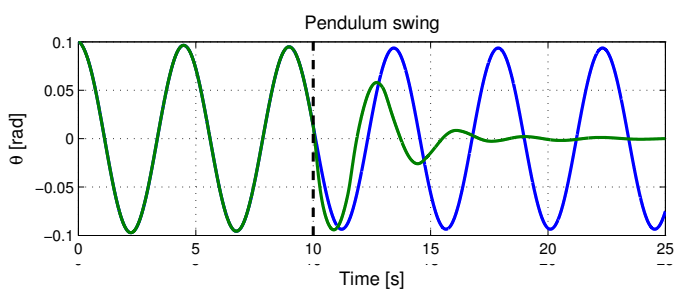

Figure 4. Cart/pendulum example. Pendulum swing angle with and without feedback controller.

II.D. Delayed Feedback for Helicopter Slung Load System

The delayed feedback control is well suited for oscillation damping in complex systems like the helicopter slung load system as it can account directly for possible delays in the signal loop. It is important to realize that this control scheme can not be used for stabilizing the helicopter or to track trajectories, but simply to dampen load swing. Therefore an inner loop controller for the helicopter is assumed as illustrated in figure 1.

The helicopter slung load system is very similar in structure to the cart/pendulum example from section II.C and we can indeed use the same approach to construct the controller. The feedback variables in the helicopter slung load system are the positions of the slung load relative to the helicopter, x_δ and y_δ (see figure 5). The output of the controller is added to the existing reference to the inner loop helicopter controller

$$\tilde{x}_r = x_r + G_d x_\delta(t-\tau) = x_r + G_d l \sin(\theta_w(t-\tau))\,, \tag{16}$$
$$\tilde{y}_r = y_r + G_d y_\delta(t-\tau) = y_r + G_d l \sin(\phi_w(t-\tau)) \tag{17}$$

as illustrated in figure 1. Given a full reference trajectory the velocity reference are found as time derivatives

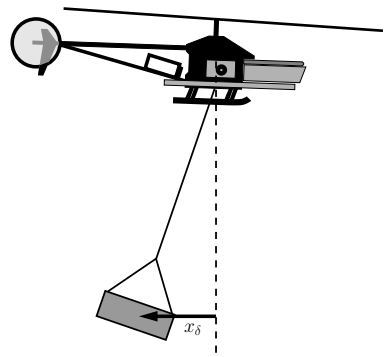

Figure 5. Relative position between helicopter and slung load.

of (16) and (17)

$$\tilde{\dot{x}}_r = \dot{x}_r + G_d l \cos(\theta_w(t-\tau_d))\dot{\theta}_w(t-\tau)\,, \tag{18}$$

$$\tilde{\dot{y}}_r = \dot{y}_r + G_d l \cos(\phi_w(t-\tau_d))\dot{\phi}_w(t-\tau)\,. \tag{19}$$

II.D.1. Design for Georgia Tech GT-Max

The GT-Max features an adaptive loop shaping controller as described in[18] which yields the following forth order translational responses

$$\begin{aligned}\frac{x}{x_r} &= \frac{K_{xp}s^2 + K_{xp}R_{xd}s + K_{xp}R_{xp}}{s^4 + K_{xd}s^3 + K_{xp}s^2 + K_{xp}R_{xd}s + K_{xp}R_{xp}}\,,\\ \frac{y}{y_r} &= \frac{K_{yp}s^2 + K_{yp}R_{yd}s + K_{yp}R_{yp}}{s^4 + K_{yd}s^3 + K_{yp}s^2 + K_{yp}R_{yd}s + K_{yp}R_{yp}}\,,\end{aligned} \tag{20}$$

where $K_{xp} = 37.5$, $K_{xd} = 10$, $R_{xp} = 1.04$, $R_{xd} = 1.66$, $K_{yp} = 24$, $K_{yd} = 8$, $R_{yd} = 0.66$, and $R_{yd} = 1.33$ are helicopter controller parameters. The slung load system is added to the model and the damping map can be calculated as shown in figure 6. Here a potential robustness problem of the design method shows

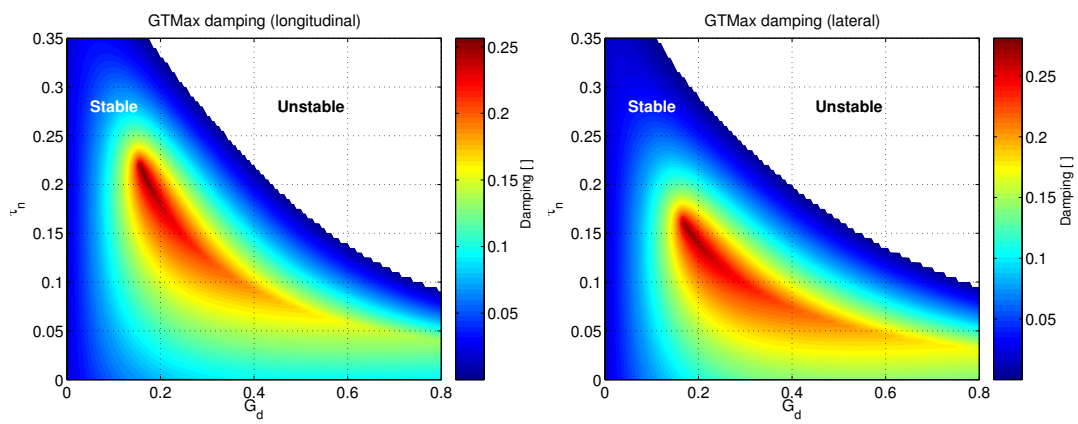

Figure 6. GT-Max design. Damping of the lateral and longitudinal helicopter slung load system as a function of delayed feedback controller parameters.

up. The method arrives at the set of control parameters that yields the maximum damping and for the cart/pendulum example shown in figure 3 this seems like a good choice as damping map is reasonably flat around the maximum damping. However, for helicopter design we can see from figure 6 that the interaction of the helicopter dynamics has resulted in a more steep damping map and that small changes for example in controller parameters can degrade the achieved damping significantly. The problem can be attended to by adding a constraint to the minimization of (10) that enforces a certain flatness around the selected point by looking at the gradient of the damping map. The desired value of flatness would then become a tuning parameter.

II.D.2. Design for Aalborg University Corona

The design for the Corona is performed similar to the process for the GT-Max, but will only be shown for the lateral dynamics. The AAU Corona is controlled by a PID control setup and its dynamic response can be described as

$$\frac{y}{y_r} = \frac{637.9}{s^4 + 13.52s^3 + 85.01s^2 + 306.7s + 673.9} \tag{21}$$

The damping map is shown in figure 7 and the delayed controller parameters can be identified as

$$G_{d,lat} = 0.15\,, \tau_{n,lat} = 0.13\,.$$

As it can be seen this damping map is significantly different from the original cart/pendulum example. This

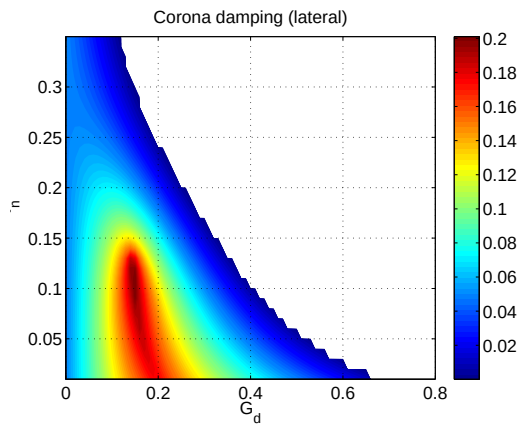

Figure 7. AAU Corona design. Damping of the lateral helicopter slung load system as a function of delayed feedback controller parameters.

is due to rather short wire length of the suspension system (1.25 m $\approx$ 2.8 rad/s) compared to the system dynamics.

III. Results

In the following we will demonstrate the effect of the controller through flight verification on the two helicopter platforms.

III.A. Flight verification: Delayed Feedback on the GT-Max

The delayed feedback controller used for these tests is a slightly detuned version of the design presented earlier in this chapter for better robustness. This was achieved by adding the gradient of the damping map to the minimization cost function. The test controller parameters yields a theoretical ζ of 0.19 in both lateral and longitudinal.

A 30 ft ($\simeq$ 9 m) aggressive lateral step without slung load control is shown to the left in figure 8 and it is clear that such a maneuver causes significant slung load swing. The right in figure 8 shows two similar steps, but this time with the delayed feedback slung load controller enabled.

The large slung load oscillation can clearly be seen on the position and velocity plots in figure 9. In figure 10 positions and velocities of the steps with delayed feedback are shown and we can see that the step maneuvers still excite the pendulous modes which result in an overshot of the slung load. As the slung load controller attempts to dampen out these oscillations, this results in an overshot of the helicopter as it tries to move with the slung load motion. After a couple of full slung load oscillations, the controller has successfully dampened out the swing. A comparison of slung load angles during the two right steps, with and without slung load controller is shown to the left in figure 11 and we can see a significant swing reduction with the slung load controller enabled. The achieved damping in the system is illustrated to the right in figure 11 where the slung load controller is enabled at $t = 0$ and quickly dampens the initial load swing. The measured slung load angles and angular velocities are plotted together the response of a

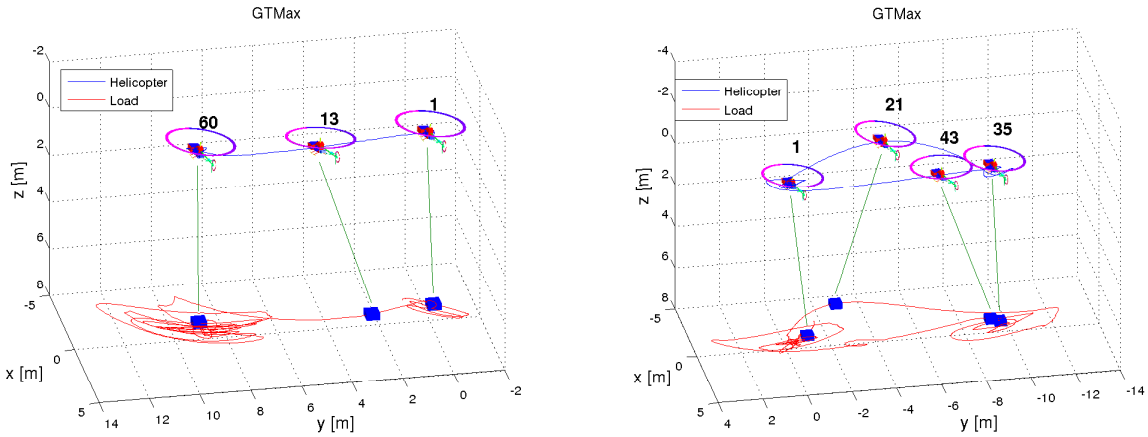

Figure 8. (Flight test) GT-Max aggressive steps. Left: One step left without slung load control. Right: Two steps (first right then left) with slung load control.

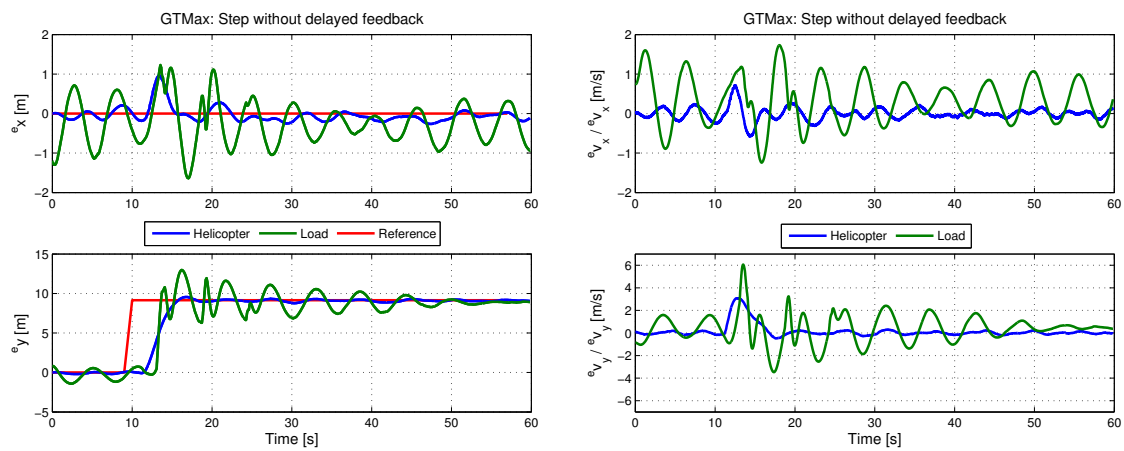

Figure 9. (Flight test) GT-Max without slung load control. Left: Helicopter and slung load position and controller position reference. Right: Helicopter and slung load velocity and controller velocity reference.

simulated pendulum with a damping of $\zeta = 0.19$ which is the predicted damping of the system. We can see how oscillation decay corresponds well with the theoretically predicted decay, but with certain discrepancies originating from helicopter motion.

III.B. Flight verification: Antiswing Control on the AAU Corona

To illustrate the damping effect of the delayed feedback controller on the AAU Corona two different 1 m lateral manoeuvres are used: A gentle and an aggressive one. The aggressive manoeuvre is simply a step in position reference, while the gentle one is an acceleration and velocity limited s-curve. The steps are performed both with and without the delayed feedback controller and a comparison is shown in figure 12. As expected the delayed controller is capable of introducing a significant damping improvement with respect to slung load swing.

Finally, to illustrate the combined effectiveness of the delayed feedback and the input shaper, an aggressive step with both controllers enabled is shown in figure 13. A ZVD input shaper is here used shape the step into a zero residual vibration maneuver as is evident on the shaped reference.[5] It can be seen the combination of actively damping swing and avoiding exciting swing during movement results in an almost swing-free motion.

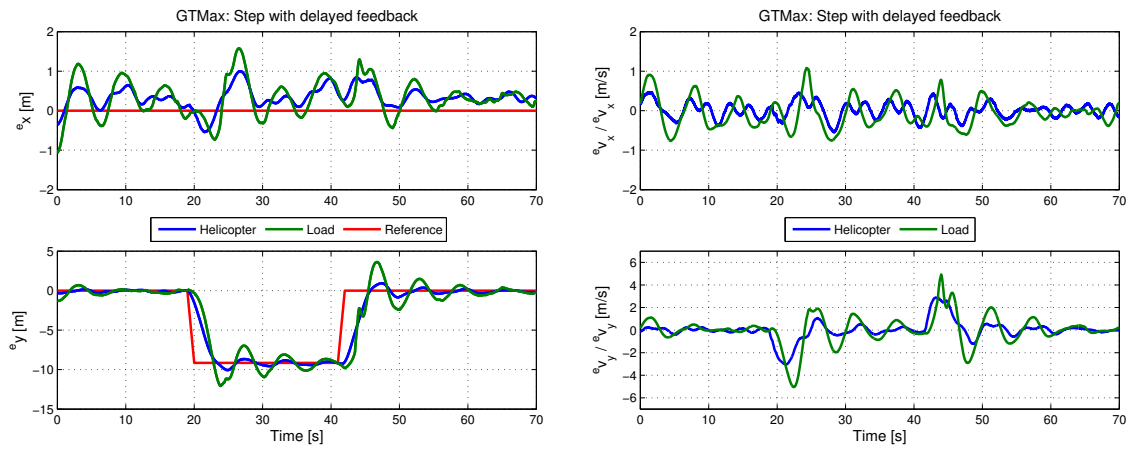

Figure 10. (Flight test) GT-Max with delayed feedback slung load control. Left: Helicopter and slung load position and controller position reference. Right: Helicopter and slung load velocity and controller velocity reference.

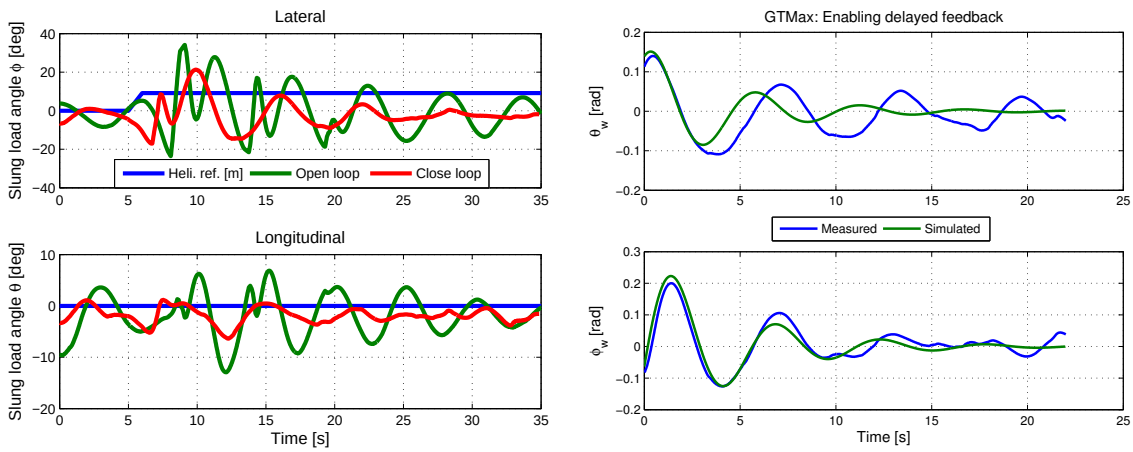

Figure 11. (Flight test) Left: Comparison of slung load swing angle lateral step with and without delayed feedback slung load controller. Right: Comparison of measured and theoretical swing damping.

IV. Discussion

In this paper a swing damping feedback control scheme was developed to improve slung load flight in autonomous helicopters. It is designed to augment helicopter stand alone controllers and together with a feedforward control scheme based on input shaping it can provide swing free slung load flight. The feedback controller is based on a delayed feedback scheme where intentional delay is introduced in the feedback loop such that feedback gain and delay are the controller parameters. Furthermore, an automated design method is formulated based on optimization. The performance of the control scheme was evaluated through flight testing on two different autonomous helicopter slung load systems and it was found that the control scheme is capable of yielding a significant reduction in slung load swing over flight without the controller scheme.

Acknowledgements

Thanks are due to everyone at Georgia Tech UAV Research Facility that supported the work on the slung load system for the GT-Max.

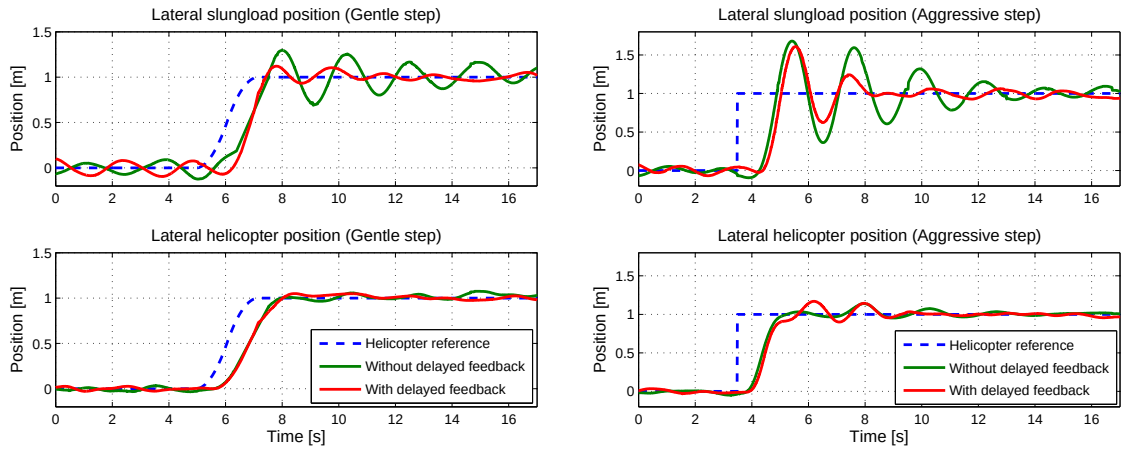

Figure 12. (Flight test) Corona 1 m gentle and aggressive lateral step with and without delayed feedback.

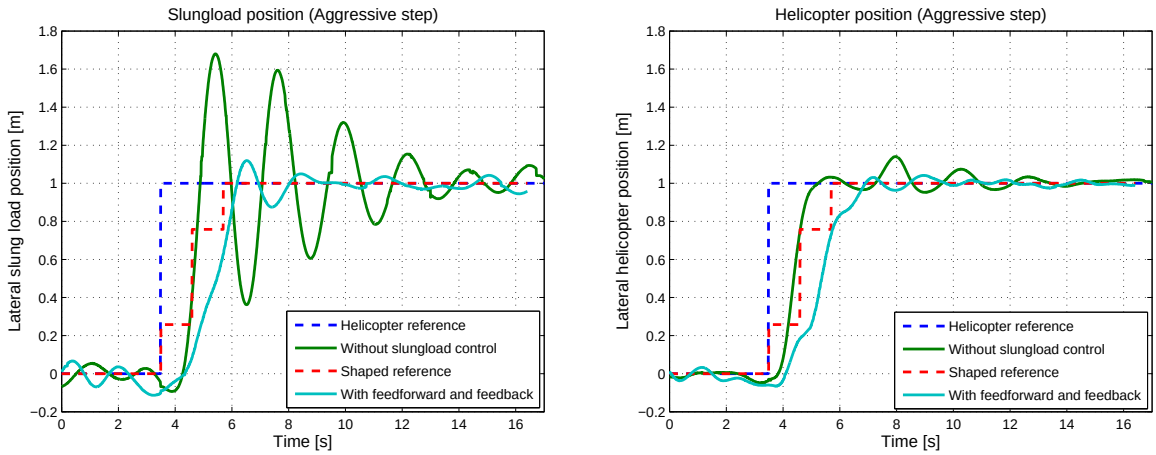

Figure 13. (Flight test) Corona 1 m aggressive step with and without delayed feedback and input shaping.

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