

DESIGN OF A THRUST VECTOR SERVOELASTIC FILTER FOR SLS BLOCK 2 BOOSTER THRUST VECTOR CONTROL SYSTEM

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This paper presents a method to improve the thrust vector servoelastic (TVSE) response of a launch vehicle. TVSE is the coupling between the Thrust Vector Control (TVC) system nozzle dynamics and the vehicle flexible modes. A poorly phased TVC response, i.e. in phase with the structural velocity, can lead to instability of the flexible modes due to the energy injection from the thrust. For large boosters with heavy nozzles, TVSE is more likely to cause instability. This instability is part of the plant dynamics and may not be readily detected by the flight control system. In this paper, TVSE is treated as a disturbance rejection problem with the inertial force of the flexible motion viewed as an external disturbance to the TVC actuator control system. By effectively rejecting this disturbance, the engine can be decoupled from the flexible dynamics thus improving TVSE stability. The actuator disturbance transfer function is modified by inserting a filter into the servo-loop control system. The filter aims to reduce the magnitude and introduce phase lead of the disturbance transfer function over the TVSE sensitive frequency range while maintaining adequate stability margins of the actuator control system. A prefilter is also designed to improve command tracking performance. The filter and prefilter resulting from this method are usually of low order and can be included to an existing actuator controller if the controller is programmable. This method was demonstrated for a hydraulic Simplex actuator model. Its applications to the Space Launch System (SLS) Block 1 and Block 2 TVC actuator are also described. The Block 2 actuator controller was modified based on the results of this method. The tradeoff between TVSE stability and the servo-loop stability can be balanced by adjusting the amount of phase lead introduced by the TVSE filter. This method provides a useful way to solve the TVSE instability issue without costly and time-consuming hardware solutions. This method is based on the basic control principles of loop shaping and disturbance rejection and has been proven to be effective under proper circumstances.

INTRODUCTION

For long flexible rocket boosters controlled using the thrust vector control (TVC), it is known that the engine rotational motion is coupled with the booster flexible modes through the dog-wags-tail (DWT) and the tail-wags-dog (TWD) (see References 1, 2 and 3) couplings. During the thruster firing, the thrust can inject energy into the flexible motion through these coupling mechanisms. When the small flexible mode damping becomes negative due to the energy injection

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from the thrust, the instability of the flexible motion occurs. This phenomenon is referred to as the thrust vector servo elasticity (TVSE). TVSE dynamics has been analyzed in the past (see References 1, 2 and 3). TVC systems with a heavier nozzle mass become more prone to the TVSE instability due to TVSE sensitivity to nozzle mass. Thus, for large boosters with higher thrusts, such as SLS Block 2, it is important to ensure that there is no TVSE instability during the ascent.

Initial Block 2 TVC system analysis exhibited negative damping of a flexible mode during the flight due to the substantially increased TVC system mass compared to the Shuttle-derived, heritage booster design employed on the Block 1 and Block 1B configurations of SLS. Even when the jet damping and nozzle ablation effects are considered, it is still not enough to stabilize the coupled flex-actuator system. A new method for mitigating the TVSE instability is needed so the costly redesign of the TVC actuator can be avoided. To answer this challenge, a simple TVSE filter is proposed to be included inside the actuator feedback control loop. By properly shaping the disturbance transfer function of the TVC control system from the DWT disturbance torque to the nozzle deflection angle in the critical TVSE frequency range, less or no energy is injected to the flex motion from the thrust, leading to positive flex damping and stable flex motion.

The paper is organized as follows. In Section 2, the theoretical analysis of the TVSE dynamics is given from which TVSE filter design requirements are derived. Following the theoretical development, Section 3 details the TVSE filter design for a Simplex TVC control system from the literature and shows the resulting TVSE filter efficacy in mitigating the flex modes negative damping. Section 4 describes the applications of this method to SLS B1 and B2 booster TVC system for TVSE improvement. Finally, conclusions are presented in Section 5.

TVSE DYNAMICS AND TVSE FILTER DESIGN PRINCIPLES

A simple analytical model can be used to investigate the flex mode damping decrement when the flexible motion is coupled with the engine dynamics. Consider one flexible mode and the engine dynamics of a rocket. Under the assumption that the commanded nozzle angle is zero, the coupled actuator-nozzle can be modeled as a mass-spring system due to the control action to maintain the zero nozzle angle. A more detailed actuator model will be used for design in the next section. This simple model of the actuator is sufficient to expose the negative damping through coupling.

The coupled nozzle-flex dynamics is represented in the Laplace form as

$$\begin{bmatrix} I_E s^2 + C_A s + k_A & \Gamma s^2 \\ \Gamma s^2 + \psi_A F & s^2 + 2\zeta_B \omega_B s + \omega_B^2 \end{bmatrix} \begin{bmatrix} \beta \\ \eta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Where I_E is the engine moment of inertia, ψ_A the flex mode shape at gimbal, C_A the actuator damping coefficient, k_A the actuator stiffness under the zero nozzle angle command, ζ_B the flex mode damping ratio, ω_B^2 the flex mode natural frequency, η the flex mode generalized coordinate, β the nozzle angle, F the thrust, and Γ is the inertial flex-engine coupling factor.

Due to the presence of the flex-engine coupling term and the thrust in the off-diagonal elements of the matrix, the nozzle motion is coupled with the flex motion. The coupled system modal frequencies and damping ratios deviate from the natural frequencies and damping ratios of the engine and the flex mode. The system is stable when there is no thrust (Reference 3); however, in the presence of the thrust, the energy from the thrust can be added to the system, such that it can become unstable.

More insights can be obtained from the equation. The first equation is the nozzle equation with DWT contributions from flex. This DWT torque term can be viewed as an external disturb-

ance that the actuator closed-loop servo will try to reject. If the controller has a high enough bandwidth, then it can completely reject this disturbance torque and the system becomes effectively decoupled. However, the DWT disturbance to the engine cannot be completely rejected. This gives the first design requirement for the TVSE filter that the magnitude of the disturbance transfer function (DTF), which is the transfer function from the flex inertial torque input to the nozzle angular displacement output, with the TVSE filter shall not be larger than that when without it.

Reference 2 investigated the phase relation between the flex velocity of the gimble in the normal direction and the thrust component in the normal direction at the TVSE resonance. When the phase difference is exactly 90 degrees, then no net work is done by the thrust during the flex oscillation. If they are in phase, the thrust adds energy into the flex motion; if out of phase, the thrust dissipates energy out of the flex motion. Thus, a favorable phasing relation between the velocity and thrust shall be created to prevent the TVSE resonance from happening. This gives the second TVSE filter design requirement: enough phase lead in the DTF around the actuator bandwidth frequencies shall be introduced by the TVSE filter.

Other requirements on the TVSE filter besides TVSE mitigation requirements are to maintain adequate stability margins against TVC system uncertainties and have good command performance of the actuator control system after adding the TVSE filter.

TVSE FILTER DESIGN EXAMPLE

Insights have been gained from the coupling mechanism and the DTF design requirements have been established. A Simplex model of a hydraulic TVC actuator of a large booster given in Reference 3 is used in this sector to design a TVSE filter for recovering the modal damping from flex-nozzle coupling based on these design requirements. It will be shown that this approach mitigates TVSE instability effectively. However, due to insertion of the TVSE filter, a prefilter is needed to filter the command angle to maintain a good tracking performance. By the nature of the closed-loop control, an improvement in the disturbance rejection leads to tradeoffs in other objectives. In this case, the open loop phase margin is decreased. By a careful design of the TVSE filter, TVSE stability can be improved along with adequate open loop phase margin of the actuator control system.

In the Simplex actuator model the piston force applied to the nozzle at the attachment point can be derived after some algebra operations

$$f_a = \frac{k_T}{A_p s} \left[-k_v k_u \frac{s}{A_p \left(s + \frac{1}{\tau_p} \right)} f_a - k_v k_x \left(d\beta + \frac{f_a}{k_L} \right) + k_v k_g \beta_c \right] - k_T d\beta$$

Where k_u is the pressure feedback gain, k_x is the position feedback gain, k_q is the command input gain, and k_v is the valve flow gain. k_T is the total stiffness, d is the actuator moment arm, β is the nozzle rotation angle, β_c is the command nozzle angle, A_p is the piston area, τ_p is the pressure filter time constant. s is the Laplace variable. All these parameter values can be found in Reference 3. The following relation has been used:

$$x_a = d\beta + \frac{f_a}{k_L},$$

where x_a is the actuator piston position which is measured for feedback use, and k_L is the load stiffness.

If a filter $F(s)$ is added for processing the feedback signal x_a , the equation becomes the following.

$$\begin{aligned} f_a &= \frac{k_T}{A_p s} \left[-k_V k_u \frac{s}{A_p \left(s + \frac{1}{\tau_p} \right)} f_a - k_V k_x F d \beta - k_V k_x F \frac{f_a}{k_L} + k_V k_g \beta_c \right] - k_T d \beta \\ &= \frac{k_T}{A_p s} \left(-k_V k_u \frac{s}{A_p \left(s + \frac{1}{\tau_p} \right)} - k_V k_x \frac{F}{k_L} \right) f_a - \left(\frac{k_T k_V k_x d F}{A_p s} + k_T d \right) \beta + \frac{k_T k_V k_g}{A_p s} \beta_c \end{aligned}$$

After moving the actuator force term in the right hand side to the left hand side and combining terms, we have

$$\left[1 + \frac{k_T k_V k_u}{A_p^2 \left(s + \frac{1}{\tau_p} \right)} + \frac{k_T k_V k_x F}{A_p k_L s} \right] f_a = - \left(\frac{k_T k_V k_x d F}{A_p s} + k_T d \right) \beta + \frac{k_T k_V k_g}{A_p s} \beta_c$$

This equation shows the actuator control law: the dynamics of the actuator force under the engine angle feedback and the angle command input. The actuator force times the moment arm is the actuator torque applied to the nozzle.

Simplifying the controller expression,

$$\begin{aligned} f_a &= C_\beta \beta + C_{\beta_c} \beta_c, \\ C_\beta &= \frac{k_T k_L A_p \left(s + \frac{1}{\tau_p} \right) (k_V k_x d F + d A_p s)}{a s^2 + b s + c} \\ a &= k_L A_p^2, \\ b &= \frac{k_L A_p^2}{\tau_p} + k_T k_V k_u k_L + k_T k_V k_x A_p F, \\ c &= \frac{k_T k_V k_x A_p F}{\tau_p}. \end{aligned}$$

The engine/nozzle EOM becomes:

$$(I_e s^2 + C_e s + K_e) \beta = d C_\beta \beta + d C_{\beta_c} \beta_c + T_d$$

Where T_d is the DWT disturbance torque on the engine.

The closed-loop response of the engine angle becomes:

$$(I_e s^2 + C_e s + K_e - d C_\beta) \beta = d C_{\beta_c} \beta_c + T_d,$$

And the DTF is

$$\frac{1}{I_e s^2 + C_e s + K_e - d C_\beta}$$

The filter F is a part of the transfer function C_β and can be used for shaping the DTF. When F is a dynamic system, the DTF is a complex function of the filter F .

To help the design of F and investigate its impacts on the control performances, express F by the numerator and denominator:

$$F = \frac{N_F}{D_F}$$

$$C_\beta = \frac{k_T k_L A_p (s + \frac{1}{\tau_p}) (k_V k_x d N_F + d A_p s D_F) / D_F}{a s^2 + b s + c}$$

$$a = k_L A_p^2,$$

$$b = \frac{k_L A_p^2}{\tau_p} + k_T k_V k_u k_L + k_T k_V k_x A_p \frac{N_F}{D_F},$$

$$c = \frac{k_T k_V k_x A_p N_F}{\tau_p D_F}.$$

Simplify and combine terms to have:

$$C_\beta = \frac{k_T k_L A_p (s + \frac{1}{\tau_p}) (k_V k_x d N_F + d A_p s D_F)}{a D_F s^2 + \left(\frac{k_L A_p^2}{\tau_p} + k_T k_V k_u k_L \right) D_F s + k_T k_V k_x A_p N_F s + \frac{k_T k_V k_x A_p N_F}{\tau_p}}$$

The DTF dynamics is very complex in terms of the TVSE filter. However, in general, F is a lead/lag filter with a gain. If a lead/lag filter is not satisfactory, more poles and zeros can be added by progressing with one change at a time and good bookkeeping. By a few trials, it is not difficult to arrive at a satisfactory TVSE filter design.

The TVSE filter was designed next to meet the requirements: no increase in the magnitude of the DTF over the TVSE sensitive frequency range; add phase lead over the TVSE sensitive frequency range; and maintain adequate open loop phase margin for robust stability. A tradeoff is made to balance the TVSE mitigation (DTF phase lead) and the closed-loop stability (open loop phase margin). Results are given next. Figure 1 shows the Bode plot of the resulting TVSE filter.

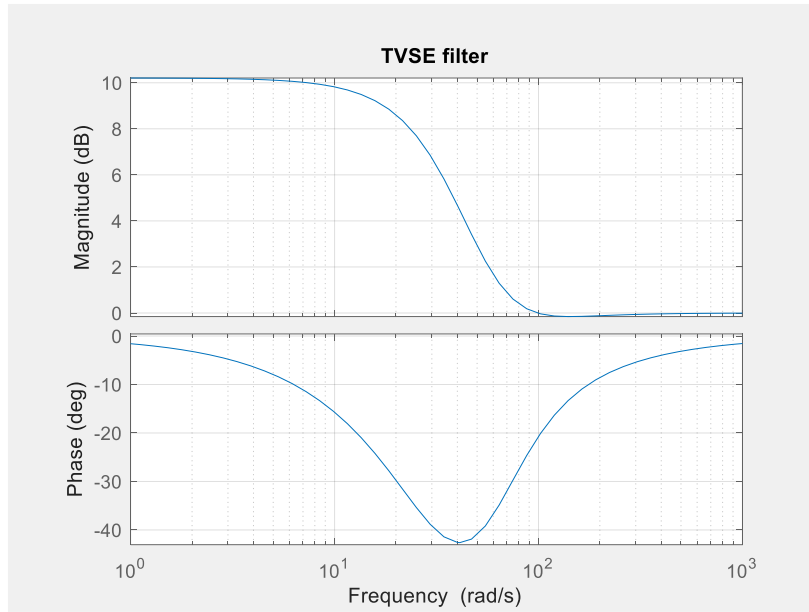


Figure 1. TVSE filter Bode plot.

Figure 2 shows the Bode plot of the DTF. The TVSE filter introduces significant phase lead over the TVSE sensitive frequency range around the actuator bandwidth frequency. The magnitude of the DTF is also smaller over the TVSE sensitive frequencies with the TVSE filter.

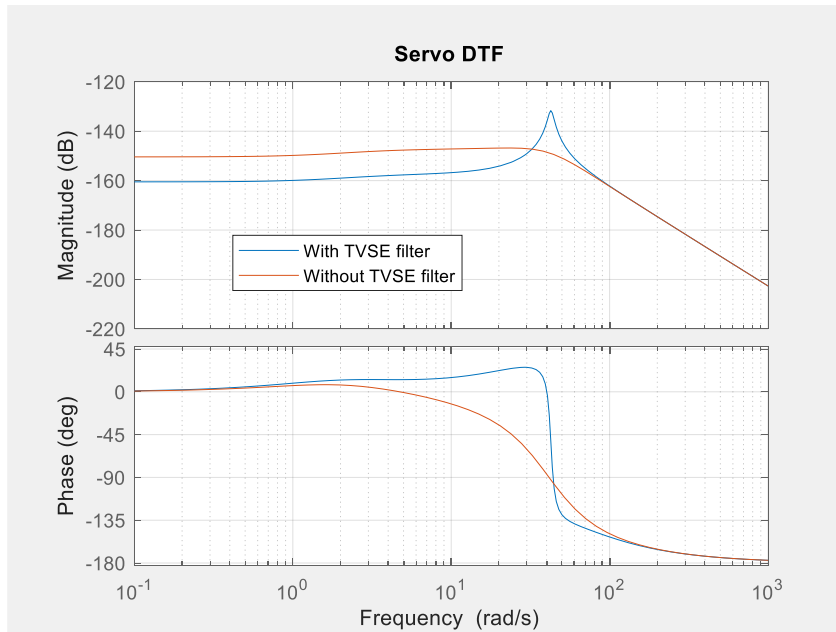


Figure 2. DTF of the TVC actuator.

Figure 3 shows the damping ratios of the flex-engine coupled system. The vertical line in the plot indicates the TWD-flex-zero frequency. The damping ratio of the flexible mode is 0.5% and the damping ratio decreases due to the energy injected into the flexible motion by the thrust

through TWD coupling. When the TVSE filter is added into the actuator control system, the damping ratio of the flexible mode is recovered to be more than 0.5%.

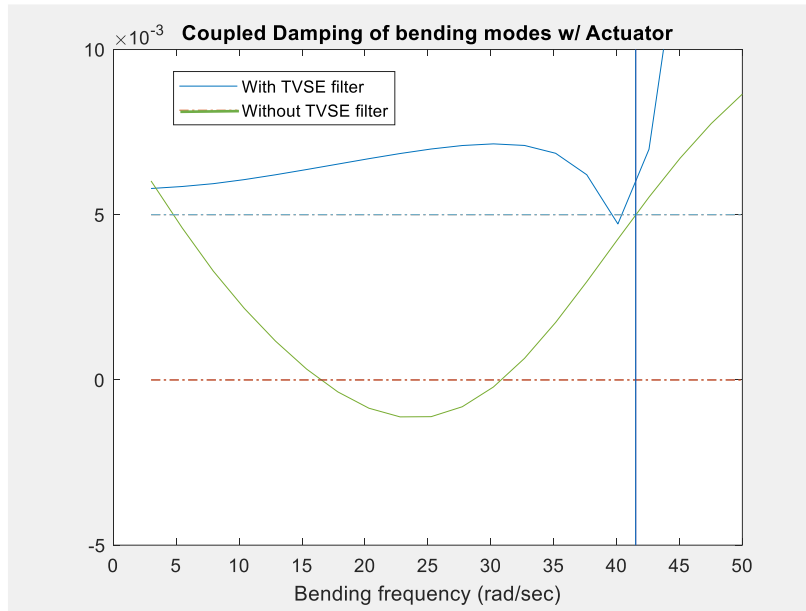


Figure 3. Damping ratio of the flexible mode.

Figure 4 shows the command step response of the actuator control system. When the TVSE filter is added into the Linear Variable Differential Transformer (LVDT) feedback, the closed-loop transfer function is modified. A prefilter is designed and applied to the angle command to have good time domain performance.

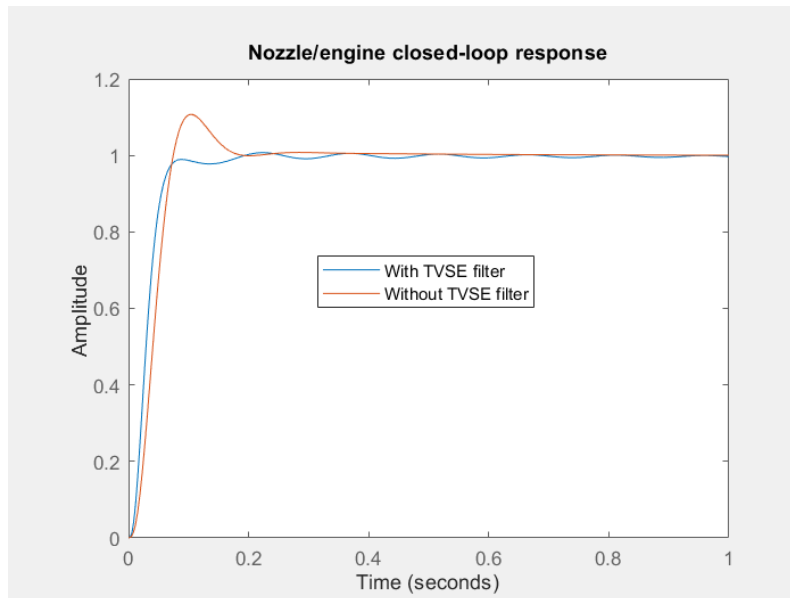


Figure 4. Actuator command step responses.

Figure 5 shows the actuator control system open loop transfer function Bode plot. Compared to the DTF shown in Figure 2, the open loop transfer function with TVSE filter has phase lag over the frequency ranger around the bandwidth where the DTF phase lead is introduced by the TVSE filter , resulting in some loss in the phase margin. The phase margin of the open loop with TVSE filter is 41degrees for the current design.

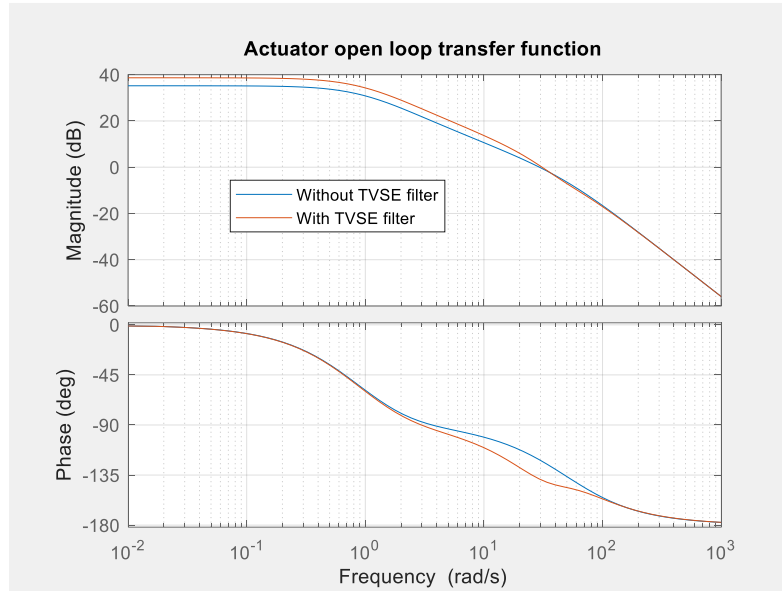


Figure 5. Actuator open loop Bode plot.

APPLICATIONS TO SLS B1 AND B2 BOOSTER TVC SYSTEM

After the proof-of-concept design was done, the proposed method was applied to SLS Block 1 booster TVC system which has a hydraulic actuator control system for proving the applicability of the method. The Block 1 booster actuator control system model is a Simplex model like the Simplex model used in the previous section but with different parameter values and extra nonlinear elements. The TVSE filter was placed in the piston position LVDT feedback path. The designed low order TVSE filter introduced about 20 degree of phase lead for the DTF at the target TVSE frequency.

Artemis I mission was successful without the indication of TVSE oscillation during the ascent where Block 1 booster was used. However, during the initial Block 2 Booster Obsolescence and Life Extension (BOLE) electric-hydraulic actuator TVC system flight analysis, negative damping of rocket flex modes was found in the stability analysis, indicating the TVSE instability. TVSE mitigations are needed without an actuator design with large costs and schedule risks. The proposed method was conceptually applied to the BOLE actuator system. The common electric-hydraulic actuator (CEHA) Simplex model provided by the TVC system vendor was used for designing the TVSE filter. The TVSE filter was again placed in the piston measurement feedback loop. A simple first order filter was designed to introduce about 10 degrees of phase lead at the target frequency of the DTF and at the same time keeping the magnitude at this frequency unchanged. The TVSE filter, combined with the jet damping was effective in reducing the severity of the TVSE stability to heritage levels. Monte Carlo simulations in both the time and frequency

domain were performed to successfully prove the robust stability and performance of the TVC system with the added TVSE filter.

So far, this paper has examined placing the TVSE filter in the actuator LVDT position feedback path. Simplex TVC actuator models also have a load pressure feedback loop and sometimes a velocity inner loop. A study was done to investigate the options of placing the TVSE filter in the pressure feedback path and inside the velocity loop. It turns out that an equivalent TVSE can be designed for the pressure feedback signal. However, it is less effective to place TVSE filter inside the velocity loop, because the compensation is more complex and less effective because the engine angle signal as a controlled target is not directly processed.

CONCLUSION

A method for improving or solving TVSE stability issue is presented. By gaining insights of the flex-engine coupling mechanism using a simple analytical model, requirements of the actuator DTF can be derived to effectively decouple the flex-engine dynamics, thus restoring the modal damping of the booster flexible modes. A hydraulic Simplex model is used as an example to demonstrate the design of a TVSE filter and a prefilter and show the effectiveness of this method. This approach is further applied to Simplex models of SLS Block 1 and Block 2 booster actuators. Block 2 actuator controller is modified based on the result of this approach for mitigating the TVSE instability issue found from previous stability analysis.

REFERENCES

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