H∞ mixed sensitivity optimization for high speed tilting trains

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ABSTRACT

The industrial norm of tilting high speed trains, nowadays, is that of Precedence tilt (also known as Preview tilt). Precedence tilt, although successful as a concept, tends to be complex (mainly due to the signal interconnections between vehicles and the advanced signal processing required for monitoring). Research studies of early prior to that of precedence tilt schemes, i.e. the so-called Nulling-type schemes, utilized local-per-vehicle signals to provide tilt action (this was essentially a typical disturbance rejection-scheme) but suffered from inherent delays in the control. Nulling tilt may still be seen as an important research aim due to the simple nature and most importantly due to the more straightforward fault detection compared to precedence schemes. The work in this paper presents a substantial extension conventional to robust H∞ mixed sensitivity nulling tilt control in literature. A particular aspect is the use of optimization is used in the design of the robust controller accompanied by rigorous investigation of the conflicting deterministic/stochastic local tilt trade-off.

Keywords:
Active suspension
Mixed sensitivity
Optimization
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1. INTRODUCTION

Tilting trains is a worldwide accepted technology concept in high speed railway transportation. It has been successfully established as a part of modern railway vehicle technology with many high-speed train services worldwide fitted with tilt [1-3] and an increasing interest for regional express trains as well as recently attempt to apply in metro systems [4]. The tilting concept is quite straightforward whereby usually a tilting mechanism (that is inverted pendulum-like platform) is employed to (mostly actively) lean the vehicle body inwards on track corners hence reducing the lateral acceleration level experienced by passengers. The particular benefit from tilting trains use is reduction in journey times due to increase of speed on track corners. From a more local (South-East Asia) area viewpoint, use of tilting service could be beneficial to the Malaysia High Speed Railway project since it presents a potentially cost effective solution to consider and hence potentially avoid building an extensive (and expensive) new rail-track infrastructure.

In most cases of high speed tilting trains, active control is used to perform the tilting action and active tilting train systems technology has been greatly improved by the major contributions of control engineering [1-2]. Initial control design attempts on tilting trains employed the so-called “nulling” tilt control approach [5], i.e. feedback control from a single lateral accelerometer mounted on the body of the vehicle (regarding required tilt) passenger vehicle. This early attempt proved to be challenging to perform sufficiently fast response on the curve transitions without causing a degradation of ride quality on (straight) track misalignment as well as system stability.

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As mentioned already nowadays tilting trains employ a command-driven system in which a signal from an accelerometer on a non-tilting part of the precedent vehicle (and sometimes from a database) commands the required tilting angle, with a straightforward tilt angle feedback controller locally ensuring that each vehicle tilts to the indicated tilt angle [6, 7]. This solution is commonly known as tilt with precedence i.e. utilise preview-tilt information from the previous vehicle with a sufficient level of filtering to be applied to remove the effect of track irregularities on the tilt command signal. Essentially tilt-with precedence attempts to improve the performance issues of “Nulling”-type. The preview-tilt approach is the currently accepted in industrial practice in tilting trains systems, but it can be a complex overall scheme; amongst other things it must reconfigure when the train changes direction, still difficult to provide a satisfactory performance for the leading vehicle of the train. It must be noted that GPS systems are used in some cases to provide the “when-to-tilt” (preview) command via track database information, although issues of signal quality communication, delays, and constraints due to tunnels may affect operation and add further complexity [1, 8, 9].

Previous studies of control applications in railway exist [10-12]. In recent publication specifically, many studies has been done before [13-15] and more recent studies in [16-18]. Although there is no depth investigation via optimization relative to tilt control interest-cost function $H_\infty$ mixed sensitivity controller design. It is proven to be difficult to achieve the trade off between deterministic and stochastic in tilt control performance via manually designed controller [7].

This paper presented, exactly this, i.e. the impact of optimizing $H_\infty$ mixed sensitivity controller in achieving improved results on the tilt control trade off between deterministic and stochastic performance via optimizing weight constraints. The controller performance is rigorously assessed using both frequency-domain and time-domain (simulation) analysis.

2. MODELLING

The simple tilting train setup use here with anti roll bar as tilt across secondary tilting mechanism. The end view vehicle is presented in Figure 1. The details mathematical expression can be referred to [16]. As expected in dynamic behavior railway system, actuator dynamics parameters systems are selected to provide damping of 50% and 3.5Hz bandwidth. Linearised version of non linear behavior system is used here as it gives good approximation for analysis and designing robust controller. The overall roll angle from the horizontal (track elevation + expected tilt) shall not exceed 14 degrees.

![Figure 1. End view of anti roll bar (ARB) tilting vehicle structure [7]](image)

The nominal transfer function from mathematical model in [16] is given by (1)
With the state vector, control input and exogenous input vectors \( -t \) are dropped for simplicity.

\[
x = \begin{bmatrix} y_v & \theta_v & y_b & \theta_b & y_\theta & \delta_t & y_w \end{bmatrix}^T, \quad u = [\delta_{\text{ti}}]
\]

The details definition of values and parameters in (2) was presented in [16]. This represent 60% tilt compensation of effective cant deficiency and ideal control input tilt angle \( \Delta_{(\theta, t)} \). From nominal transfer function in (1), it is noticeable that the existence of non minimum phase (NMP) zeros located at 29.36 and 6.02. It is well known that the existence of NMP zeros on the right hand plane will constraint the bandwidth. It is difficult to design good and robust controller due to this NMP zeros location that is close to origin. There are two exogenous inputs used as assessments in this model, (i) deterministic track input and (ii) straight track misalignment in lateral direction also known as stochastic track input [19]. The stochastic track input velocity spectrum is represented by,

\[
S_T(f_s) = \frac{(2\pi)^2\Omega_s^2v^2}{f_s^2}(\text{m/s})^2 \text{Hz}^{-1}
\]

Where \( v \) is the vehicle speed (58 m/s – 30% higher than non-tilt) and \( f_s \) is the temporal frequency in Hz. For simulation purpose, the value of \( \Omega_s \) is chosen according to typical medium-quality rail track which is \( 0.33 \times 10^{-8} \text{ m} \). For deterministic track inputs a rail track corner with maximum cant angle \( \theta_a^{\text{max}} \) of 6 degree, maximum curve radius \( R_{\text{max}} = 1 \text{ km} \), transition length = 145m at each end and track length of 1.2 km are used in simulation process. The weight lateral acceleration of passenger by \( w_2 \) Sperling index is assessed for ride quality purpose [20].

2.1. \( H_\infty \) MIXED SENSITIVITY CONTROLLER DESIGN

The \( H_\infty \) mixed sensitivity controller design is useful in order to achieve robust control performance. With a robust design, the stability of the system in nominal plant can be achieved. In tilt control especially, manual design of \( H_\infty \) mixed sensitivity was investigated in [21]. However, it is proven that by using manual design, the tilt control performances trade off are difficult to achieved. Here, the SISO advanced (integer-order) robust approach is extended by using optimization in tuning the related weighting functions for the \( H_\infty \) mixed sensitivity design. The feedback structure of the proposed controller designed is shown in Figure 2.

\[ G(s) = \frac{Y_{\text{feed}}}{\dot{\theta}_a} = \frac{(s-6.02)(s^2 + 7.65s + 24.44)(s^2 + 4.825s + 15870)}{(s^2 + 23.2)(s^2 + 5.1s + 88.02)} \tag{1} \]

\[
2753(s + 2618)(s + 4073)(s - 29.36) \tag{1}
\]

\[
\begin{align*}
G(s) &= \frac{Y_{\text{feed}}}{\dot{\theta}_a} = \frac{(s-6.02)(s^2 + 7.65s + 24.44)(s^2 + 4.825s + 15870)}{(s^2 + 23.2)(s^2 + 5.1s + 88.02)} \\
&= \frac{(s^2 + 22s + 4836)(s^2 + 29.15s + 4888)}{(s^2 + 23.2)(s^2 + 5.1s + 88.02)}
\end{align*}
\]
Here, we designed $W_3$ as multiplicative uncertainty bound covers NMP zeros in (1) based on the previous paper by [19]. This bound is illustrated in Figure 3. $W_1$ and $W_2$ is obtained via optimization. We presented two cases of optimization, $P_1$ (all the weight sensitivity are included in the optimization process) and $P_2$ where $W_3$ is excluded.

$$W_3(jw) = \frac{-j70.76w}{(176.7 - w^2) + j35.38w}$$

$$W_i = \frac{(s/(M^{1/2})) + W_{gs}}{(s + W_{gs}(A^{1/2}))}$$

The second order transfer function formula for $W_i$ in (6) was introduced by [22, 23] where $W_{gs}$ is maximum frequency bandwidth, M is the maximum peak of Sensitivity ($S(jw)$) and A is maximum steady state error. The initial value of upper and lower bound of $W_i$ was obtained from previous PID design by [24, 25]. The presented framework is designed to have closed-loop stability, good tracking or disturbance rejection performance and robust stability. However, robust performance analysis assessment will not be included in this paper. The optimization process is implemented via fmincon() in MATLAB. The minimization problem for $H_{\infty}$ mixed sensitivity is given by,

$$\text{Minimize } f(x) = P_{cr \text{ standing}}$$

$$\text{Subject to } \left< \text{constraint=rdq} \leq 7.5\% \right>$$

Where $P_{cr \text{ standing}}$ is the percentage of standing passengers feeling uncomfortable on curve transition and r.d.q is ride degradation quality compared to non tilting trains based on Europe standard [20]. The results of tuned weight sensitivity via optimization is presented in Table 1.

| Minimization ID | $W_1$ | $W_2$ | $W_3$ |
|-----------------|-------|-------|-------|
| $P_1$           | $s^2 + 1.317s + 0.4337$ | $1.255s^2 + 0.06102s + 0.0007416$ | 0.9355 | as in eq. (5) |
| $P_2$           | $s^2 + 3.06s + 2.341$ | $2s^2 + 0.1375s + 0.00236$ | 0.7043 | NA |

$H_{\infty}$ mixed sensitivity optimization for high speed tilting trains (Fazilah Hassan)
3. RESULTS AND ANALYSIS

The nominal tilt performance and performance margins for both $P_1$ and $P_2$ with full order controller is presented in Table 2 and Table 3. The results for both cases shows very satisfactory and improved tilt performance compared to the one presented in [24, 25]. By not including complimentary sensitivity in optimization problem, $P_2$ gives better $P_{CT}$ performance for both standing and seating (less is better in this case). Also for both cases, less than 7.5% ride quality degradation is obtained. Both trade-off between deterministic and stochastic that is difficult to achieved via manual design can be achieved via $H_{\infty}$ mixed sensitivity optimization.

| $H_{\infty}$ mixed sensitivity optimization | $P_1$ | $P_2$ |
|-------------------------------------------|-------|-------|
| Standing (% of passeng.)                   | 48.703| 46.41 |
| Seated (% of passeng.)                     | 13.029| 11.912|
| Tiling train                               | 3.059 | 3.052 |
| Degradation (passenger comfort)            | 7.413 | 7.166 |

Table 3. Performance margin

| Cases | $P_1$ | $P_2$ |
|-------|-------|-------|
| Gain margin (dB)                  | 8.306 | 6.243 |
| Phase margin (deg)                | 52.682| 44.513|
| Bandwith (rad/s)                  | 1.25  | 1.23  |
| $\|S(j\omega)\|_\infty$          | 1.625 | 1.925 |

Stable performance margins can be seen on Figure 4. Both cases show satisfactory open loop response with satisfies gain and phase margin. In term of lateral acceleration, $P_2$ case perform faster than $P_1$. This can be see in Figure 5.

![Nichols Chart](image1)

(a)

![Nichols Chart](image2)

(b)

Figure 4. Open loop frequency response for $P_1$ (a) and $P_2$ (b)

Although in nominal performance with the introduction of complimentary sensitivity $W_f$ less superior compared to $P_2$ case, it is expected to gives better robust performance. More conservative controller designs tend to provide better robust performance but can be far from the desired aim of improving Nulling-type tilt control performance.
4. CONCLUSION

This paper has presented an optimized viewpoint of $H_{\infty}$ mixed sensitivity design for tilt control (emphasizing the single input single output(SISO) problem aspect in this application). The impact of the proposed controller in nominal performance was showcased via extensive simulation results. With the presented benefits of proposed controller with respect to tilting train control performance, the (optimized) $H_{\infty}$-mixed sensitivity controller design approach can be applied to other active suspension vehicle problems. Future points of interest relating to the extension of this work are controller reduction (while maintaining robust performance) considering a gain-scheduled framework.

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