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Determination of Close Loop System Stability in Automobile Adaptive Cruise Control Systems

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ABSTRACT: *The beginning of the 21st century sees auto makers pursuing research in advanced features like collision warning and avoidance system into their product. Automotive cruise control system has been undergoing development in EU since the PROMETHEUS programme in the late 1980's, and has currently metamorphous into Adaptive Cruise Control (ACC) technology which is presently emerging in the automotive market as a convenience function intended to reduce driver workload. Adaptive cruise control is the first of the new generation of advanced driver's assistance devices to reach the market, which partially automates the driver's task and bringing the drivers comfort into perspective. It allows the host vehicle to maintain a set speed and distance from preceding vehicles by a forward object detection sensor. The forward object detection sensor is the focal point of the ACC system, which determines and regulates vehicle acceleration and deceleration through a powertrain torque control system and an automatic brake control system. This study presents overview of adaptive cruise control system, operation principles and the advantages of integrating ACC system in automobiles. Also, the system must be stable for optimum performance, and stability of a close loop system which the cruise system is an example, was determined by calculating the controller gain (K_1, K_2, K_3) and substituting into the characteristic equations. The stability of a close loop system for the values of K_1, K_2 and K_3 when substituted into the characteristic equation produced a negative real part. To achieve stability in close loop systems, all the poles must have negative real values and this is in line with the values obtain for p_1, p_2 and p_3. From the pole zero plots of p_1 = (-7 $\pm$ 7.14), p_2 = (-7 $\pm$ 11.60) and p_3 = (-0.08 and -13.91), stability of the system was achieved.*

Keywords: *Close Loop System, Cruise Controller, Car Speed, Stability, Traffic Condition*

I. INTRODUCTION

Adaptive cruise control also known as speed control or autocruise is a system that adequately maintains the driver's desired set speed, without any intervention by the driver, by actuating and controlling the throttle accelerator pedal linkage. In other words, the system takes over the throttle of the car and maintains a steady speed limit desired by the driver. Depending on the driver's choice of speed, cruise control system can controls the speed of a vehicle the same way a driver does, by adjusting the throttle position [3]. According to Hunter [2], adaptive cruise control (ACC) system when activated in a vehicle takes into consideration the traffic condition and controls the car accordingly. ACC system does not only operate by maintaining the pre-set of a car like conventional cruise control systems, but also maintains a constant distance between the car and the vehicle ahead by adapting to the traffic condition of the road. When the setting is programmed to operate on a certain set point (desired speed) as shown in the control loop block diagram in Figure 1, further response (illustrated by the dotted and bold arrows in the Figure 1) occurs sequentially to fully provide the necessary feedback needed to initialise the operation.

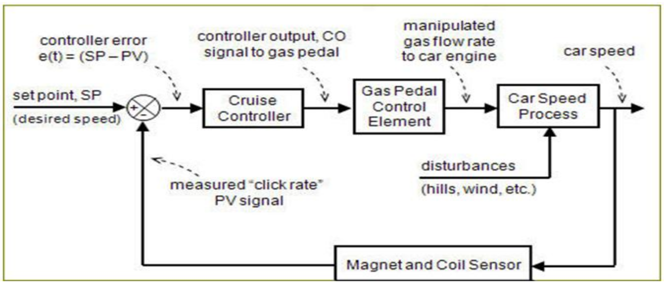

Figure 1: Car Cruise control Loop Block Diagram [1]

Cruise control actuates the throttle valve by a cable connected to an actuator. The throttle valve controls the power and speed of the engine by limiting how much air the engine takes in [7]. As shown in Figure 2, two cables can be seen connected to a pivot that moves the throttle valve. One cable comes from the accelerator pedal, and one from the actuator.

Figure 2: Cruise Control Acceleration and Deceleration [4]

When the cruise control is engaged, the actuator moves the cable connected to the pivot, which adjusts the throttle; but it also pulls on the cable that is connected to the gas pedal. Hence, this is why the pedal in a vehicle moves up and down when the cruise control is engaged. According to Nice [4], Cruise control is very essential in automobile, as long distance journeys would be more tiresome or boring for drivers or people who are suffering from fatigue or lead-foot syndrome. Cruise control is far more common in American cars than European cars, because the road network in America is wide and straight compared to road network in most European countries [6]. However, with increasing traffic condition, cruise controls may be less useful, but instead of becoming obsolete and ineffective, cruise control systems are adapting to this new reality which is the main objective of adaptive cruise control systems [5]. Nowadays, the new generation cars are designed with adaptive cruise control system otherwise known as autonomous or active cruise control, which by means of sensors allows the car to follow other cars in the queue while constantly adjusting the speed to maintain a safe distance. Adaptive cruise control system does not only maintain a set speed or distance when the vehicle is in operation, but can also prevent road accident in high ways [6]

II. METHODOLOGY

Considering the close loop transfer function of a typical ACC system as shown in Figure 3, the stability of a close loop system was calculated for K_1, K_2 and K_3 and the values obtained were substituted into the characteristic equation to generate real values to determine whether or not the ACC close loop system in this study is stable. This was carried out for peak overshoot with a step of 15% and Damping ratio of $\xi = 0.7$.

2.1. Close loop ACC System

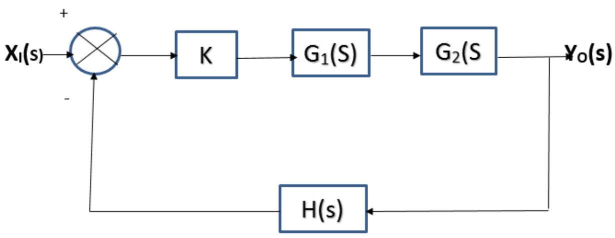

Figure 3: Close Loop Transfer Function of a Typical ACC

From figure 3,
$G_1(S)$ = Transfer function of an actuator
$G_2(S)$ = Transfer function of a plant
H (S) = Transfer function of a measurement plant
$G_O(S)$ = Open loop transfer function
G_{cl} = close loop transfer function
The transfer function of the closed loop is:

$$G_{cl} = \frac{Y(S)}{X(S)} = \frac{KG_1(S)G_2(S)}{1+KG_1(S)G_2H(S)} \quad (1)$$

Where $G_1(S) = \frac{1}{S+12}$ $\quad G_2(S) = \frac{10}{S+2}$ $\quad$ H(S) = 1
Substituting the following values in equation (1) we have;

$$G_{cl} = \frac{Y(S)}{X(S)} = \frac{K\left[\left(\frac{1}{S+12}\right)\left(\frac{10}{S+2}\right)\right]}{1+K\left[\left(\frac{1}{S+12}\right)\left(\frac{10}{S+2}\right)\times 1\right]} = \frac{10K}{S^2+2S\ 12S+24} \div 1 + \frac{10K}{S^2+2S+12S+24}$$

$$= \frac{10K}{S^2+14S+24} \div \frac{S^2+14S+24+10K}{S^2+14S+24} = \frac{10K}{S^2+14S+24} \times \frac{S^2+14S+24}{S^2+14S+24+10K}$$

$$G_{cl} = \frac{10K}{S^2+14S+24+10K} \quad (2)$$

2.2. Damping ratio of $\xi = 0.7$

Using this equation $G(S) = \frac{K}{S^2+2\xi\omega_n S+\omega_n^2}$ (3)

And comparing it with equation (2), we have

$2\xi\omega_n = 14$ (4)

$\omega_n^2 = 24 + 10k$ (5)

Substituting a damping value of $\xi = 0.7$ in equation (4) we have;

$2(0.7) \times \omega_n = 14$

$1.4\omega_n = 14$

$\omega_n = \frac{14}{1.4} = 10$ by substituting the value of ω_n in equation (5) we have

$10K = \omega_n^2 - 24 = 10^2 - 24 = 76$

$K_1 = \frac{76}{10} = 7.6$

2.3. Peak overshoot of 15% step

Peak overshoot = $exp\left(\frac{-\pi\xi}{\sqrt{1-\xi^2}}\right)$ (6)

$0.15 = exp\left(\frac{-\pi\xi}{\sqrt{1-\xi^2}}\right)$ by taking logarithm of both sides we have;

$\text{In}0.15 = \left(\frac{-\pi\xi}{\sqrt{1-\xi^2}}\right) = \frac{-\pi\xi}{\sqrt{1-\xi^2}}$ by cross multiplying we have

$\text{In}0.15\left(\sqrt{1-\xi^2}\right) = -\pi\xi$

$3.5991(1-\xi^2) = (-\pi\xi)^2$

$3.5991 - 3.5991\xi^2 = \pi^2\xi^2$ by collecting like terms we have

$3.5991 = \pi^2\xi^2 + 3.5991\xi^2 = \xi^2(\pi^2 + 3.5991)$

$\xi^2 = \frac{3.5991}{\pi^2+3.5991} = \frac{3.5991}{13.469} = 0.2672$

$\xi = \sqrt{0.2672} = 0.5169$

$\xi = 0.5169$ by substituting the value of $\xi = 0.5169$ in equation (4)

We have $2(0.5169)\omega_n = 14$

$1.033\omega_n = 14$

$\omega_n = \frac{14}{1.033} = 13.55$

By substituting the value of ω_n = 13.55 in equation (5) we have;

ω^2 = 24 + 10K
10K = ω^2 - 24

K = $\frac{13.55^2-24}{10}$ = K$_2$ = 15.96
Settling time of 4 seconds within 2% accuracy of the steady-state value for a system with damping ratio of 0.7
Using the equation $t_s = \frac{3}{\xi\omega_n}$ (7)
Making ω_n the subject of the formula we have;
$\omega_n = \frac{3}{4\times 0.7}$ = 1.071
Substituting the value of $\omega_n = 1.071$ in equation (5) we have;
ω_n^2 = 24+10K ∴ K = $\frac{\omega_n^2-24}{10} = \frac{1.071^2-24}{10}$ =
Therefore, K$_3$ = -2.285

2.4. Steady state error for a unit step

$$e_{ss} = \lim_{s\to 0}\left[\frac{1}{1+G_o(s)}\right] \tag{8}$$

The open loop transfer function is:

$$G_o(s) = \frac{10K}{S^2+14S+24} \tag{9}$$

$$e_{ss} = \lim_{s\to 0}\left[\frac{1}{1+\frac{10k}{S^2+14S+24}}\right] = \lim_{s\to 0}\left[\frac{1}{1+\frac{10k}{(0)^2+14(0)+24}}\right] = \left[\frac{1}{1+\frac{10k}{24}}\right] = \left(\frac{1}{\frac{24+10k}{24}}\right) = \frac{24}{24+10k}$$

$$e_{ss} = \frac{24}{24+10k}$$

Substituting into the steady-state error of the system the three values of ''K'' obtained above in No 2 of section 2 above we have;
(a) K$_1$ = 7.6
(b) K$_2$ = 15.96
(c) K$_3$ = -2.285

For the first, second and third value of K we have;
(a) $e_{ss} = \frac{24}{24+10(7.6)} = \frac{24}{100} = 0.24$
(b) $e_{ss} = \frac{24}{24+10(15.96)} = \frac{24}{183.6}$ 0.131
(c) $e_{ss} = \frac{24}{24+10(-2.285)} = \frac{24}{1.15} = 20.86$

2.5. Using Routh-Hurwitz to determine K

$G_{cl} = \frac{10K}{S^2+14S+24+10K}$
From the equation $S^2 + 14S + 24 + 10K$
a_0 = 1
a_1 = 14
a_2 = 24
a_3 = 10k

$$\begin{array}{c|cc|} S^2 & 1 & 24 \\ S^1 & 14 & 10K \\ S^0 & \frac{14\times 24-10K}{14} & \end{array}$$

The value of K is:
24 - $\frac{10K}{14} > 0$ $\frac{10K}{14} > 24$ $10K > 336$ $K > \frac{336}{10} > 33.6$ $K > 33.6$
The system is stable since the first column of the Routh–Hurwitz is positive

2.6. The poles of a closed loop system

$S^2 + 14S + 24 + 10K = 0$
Substituting the value of $K_1 = 7.6,\ K_2 = 15.96, K_3 = -2.285$ in the characteristic equation we have;
$S^2 + 14S + 24 + 10K = 0$
For K_1 = substitute in the equation below

$S^2 + 14S + 24 + 10(7.6) \; = S^2 + 14S \; + 100 = 0$
The root of an equation is given by;
Root = $\frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$ and so the root of the denominator of the transfer function are;
$p_1 = \frac{-1 \pm \sqrt{(14^2 - 4 \times 1 \times 100)}}{2 \times 1} = \frac{-14 \pm \sqrt{(-204)}}{2} = -7 \; \pm 7.14j$
$p_1 = -7 \; \pm 7.14j$
For $K_2 = 15.96$ we have
$S^2 + 14S + 24 + 10 \times (15.96) = S^2 + 14S + 183.6 = 0$
$p_2 = \frac{-14 \pm \sqrt{(14^2 - 4 \times 1 \times 183.6)}}{2 \times 1} = \frac{-14 \pm \sqrt{196 - 734.4}}{2}$ = -7 $\pm$ $11.60j$
p_2 = -7 $\pm$ $11.60j$
For K_3 = - 2.285 we have from the characteristics equation
$S^2 + 14S + 24 + 10 \times (-2.285) = S^2 + 14S + 1.15 = 0$
By using the almighty formula pole p_3 becomes
$p_3 = \frac{-14 \pm \sqrt{(14^2 - 4 \times 1 \times 1.15)}}{2 \times 1} = \frac{-14 \pm \sqrt{(196 - 4.6)}}{2} = \frac{-14 \pm \sqrt{191.4}}{2}$
$= \frac{-14 \pm 13.83}{2}$
p_3 = -0.08 and -13.91
Creating the Pole-Zero Plot on the Complex Plane (S-Plane), we have;
(a) p_1 = -7 $\pm$ 7.14
(b) p_2 = -7 $\pm$ 11.60
(c) p_3 = -0.08 and -13.91
Pole-Zero Plot on the Complex Plane (S-Plane) is graphically represented as shown in Figure 4, 5 and 6.

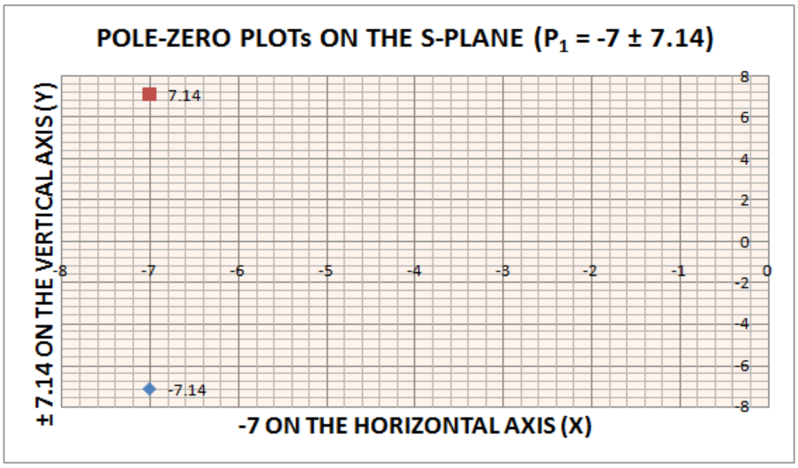

Figure 4: Pole-Zero Plots on the S-Plane P_1 = -7 ± 7.14

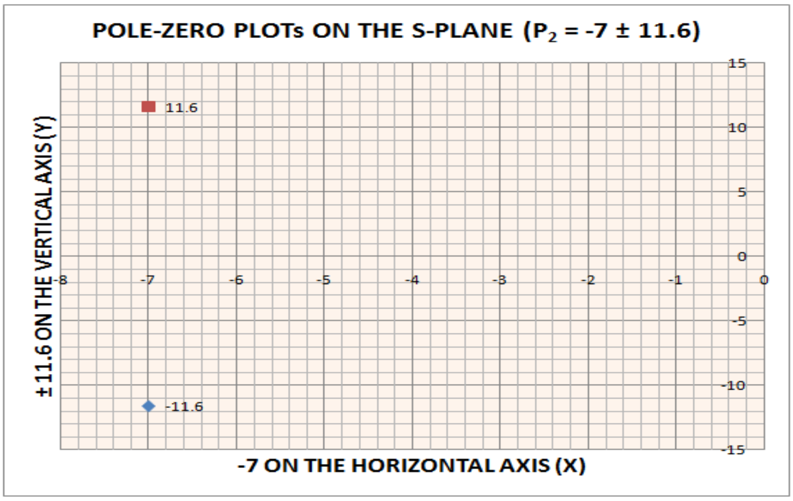

Figure 5: Pole-Zero Plots on the S-Plane P_2 = -7 ± 11.6

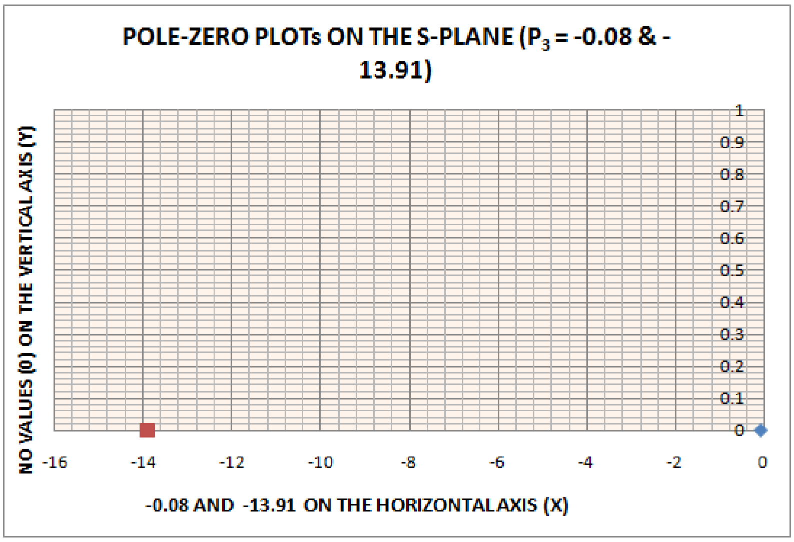

Figure 6: Pole-Zero Plots on S-Plane P_3 = -0.08 & -13.91

III. DISCUSSION

The stability of a close loop system for the values of K_1, K_2 and K_3 when substituted into the characteristic equation produce a negative real part with no zeros .For stability to be achieved, all the poles must have a negative real values which is in line with the values obtain p_1, p_2, and p_3. Observing pole zero plots for p_1, p_2 and p_3. The system is stable.

IV. CONCLUSION

The history of automotive intelligent cruise system gave an insight to how research that have started close to a decade ago, in the area of assisting tired drivers travelling over long distance arrive their destinations safely without road accidents. It has also given opportunity for discovery in such systems that aid driving. Systems such as Adaptive cruise control and intelligent cruise control adapts to traffic condition and road network and enable drivers adjust a set speed range for the car to drive by itself without colliding with the cars in front, provided the control loops of the cruise system is stable. This study has showed that, the Close Loop System in Adaptive Cruise Controls is stable when all the poles p_1, p_2 and p_3. have negative real values. However, the ACC close loop system must remain stable for proper performance, and this study has given an insight on the risk of instability of the system and how to go about achieving the system.

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