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System Design Process Integration of Cable-Drive Glass Guidance System using Axiomatic Design

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Abstract

A glass guidance system of a vehicle door window has simple functional requirements: *1) Raise and drop the window glass with a reasonable speed, 2) Stall the motor when the glass hits an object or header of the door*. There are two different glass guidance systems [1 – 4] available in market: cable-drive system and cross arm system. The cable-drive glass guidance system has been widely used over the cross-arm system due to the benefits of low-cost and light-weight while meeting the functional requirement. Even though the top-level functional requirement is simple, the system physical hierarchy is complex due to many factors involved. Also, it is crucial to identify the transfer functions due to noise factors such as temperature, humidity and manufacturing variation.

To evaluate the sensitivity and establish the system physical hierarchy, a system-level Computer-Aided Engineering (CAE) model has been built to analyze and design the glass guidance system. The influence from each subsystem on the system performance could be estimated. Quality analysis methodologies could then be applied to ensure design robustness. Besides evaluating the system performance, the CAE model is used to develop design processes. In this paper, a design process for cable-drive glass guidance system is presented. The procedure to cascade the specification of system level performance to individual subsystem design criteria is illustrated.

1 INTRODUCTION

A glass guidance system of a vehicle door window is a device installed between the vehicle door panels and has a simple top level functional requirement: 1) *Raise and drop the window glass with a reasonable speed, 2) Stall the motor when the glass hits an object or header of the door.* A typical cable-drive glass guidance system is shown in Figure 1. The entire system consists of four major subsystems, which are metal panels (door in white), seal, glass, and regulator. Glass movement is driven by a steel cable powered by either manual effort or an electric motor, which provides required torque to overcome friction within regulator mechanism, friction between glass and seal, and glass weight. The required torque is of interest.

Seals are attached at four locations of the sheet metal to provide insulation for noise and water leaking. These locations are classified as header, front run-channel, rear run-channel, and belt-line. The window glass moves up and down through the space between the inner seal and outer seal of belt-line, while its front and rear edges embed between the inner seal and outer seal of run-channels. The header seal provides insulation for the top edge of glass when the glass is in fully up position. Seals not only provide insulation to noise and water leaking but also create friction on the glass, which resists glass movement.

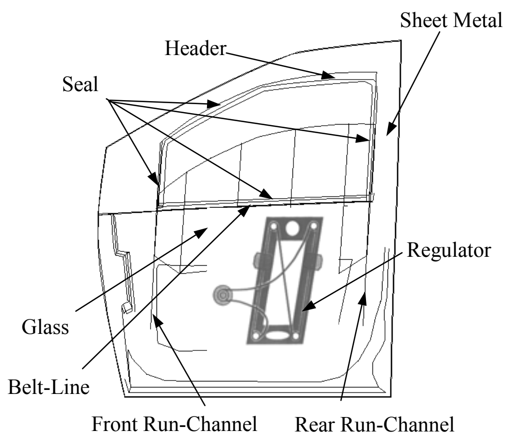

Figure 1. Typical Integrated Dual-Cable Glass Guidance System

An integrated dual-cable regulator is shown in Figure 2. Glass movement is driven by a regulator subsystem through two carriers, which are driven by a steel cable to move along two guidance rails integrated in a steel base. An electric motor or a manual crank powers movement of the steel cable. The steel cable goes through a plastic tube at the locations adjacent to the motor or crank. Carriers are attached to the guidance rails and able to slide with the steel cable along the rail's tangent direction. Two major performance requirements of glass guidance system should be satisfied for a power window. First, the time for the glass to move from its fully down position to its fully up position should be less than a certain limit. Second, the maximum motor output force should not cause component failures or create unreasonable risk of injuring the occupants of vehicles. For a manual window, the maximum effort to move glass is specified, which is not covered in this paper.

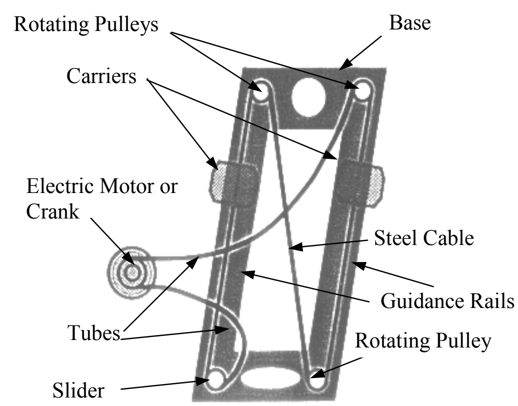

Figure 2. Integrated Dual-Cable Regulator

2 SYSTEM BACKGROUND

An overview of the system load breakdown of glass guidance system is shown in Figure 3. As shown in Figure 3, three Curves (A, B, and C) represent three probability density functions of performance. Curve A represents the probability density function of the required torque to move the glass up, which results from the combination of seal friction load, glass weight, and regulator friction. The plot regarding motor performance curves shows the mean value of motor performance (solid line) together with a ± 3σ band (dashed line). Based on the door geometry, the required minimum glass travel speed is determined by dividing the glass travel distance by the allowable maximum travel time. The minimum glass travel speed is then converted into motor RPM based on the motor drum radius. The probability density function of available motor torque is determined by intersecting the "Required RPM" line and the motor perform curves, which is represented by Curve B. Any overlay of these two curves (A and B) indicates the glass could not be moved up in the specified time limit.

Curve C' represents the motor stall load, at which motor rpm is equal to zero. The available system stall load (Curve C) is determined by subtracting the required system load (Curve A) from the motor-provided stall load (Curve C') as

Curve C = Curve C' – Curve A

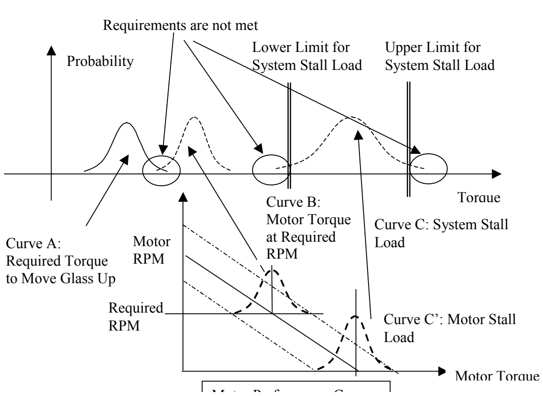

Figure 3. System Load Breakdown

There are two design criteria for the system stall load (Curve C). In order to ensure the glass is fully inserted into the header seal, the system stall load should exceed a minimum load requirement. On the other hand, the allowable maximum system stall load should not exceed the limit established based on occupant protection and component strength. The analysis process is rather

Figure 3. System Load Breakdown

[illegible] n geometric data, material properties and performance chart of selected motor, the system performance can be evaluated with the developed CAE model [5,6]. However, designers are also seeking the design guidelines to begin with. The design guidelines for the subsystem should be derived from the system level performance assessment to achieve a viable and robust system design. Utilizing axiomatic design together system CAE model, the specification of system level performance is transferred into individual subsystem design criteria that are preferred by the designers.

3 AXIOMATIC DESIGN AND MATH MODEL

The top level of design matrix is expressed as

$$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \end{bmatrix} \quad (1)$$

Where,
FR1: Glass travel time
FR2: System stall load
DP1: System required torque
DP2: Motor torque at stall

The top-level function design matrix indicates a decoupled system as shown in Equation (1). Since DP2 is one of the motor characteristics, it is not further decomposed. However, there are lots of sub-design parameters that affect the DP1. It is, therefore, very critical to identify the complete hierarchy of DP1. The hierarchy of DP1 is illustrated in Fig. 4. As shown in Fig. 4, DP1 has two independent sub design parameters; 1) regulator efficiency, 2) door window system.

Hence the transfer function for DP1 can be expressed as

$$T = F(f1, f2, \eta) \tag{2}$$

The carrier forces f1, f2 and regulator efficiency η are expressed in terms of design parameters as

$$f_1 = f_1(\delta_1, \delta_2, \mu_s, k, w, \lambda) \tag{3}$$

$$f_2 = f_2(\delta_1, \delta_2, \mu_s, k, w, \lambda) \tag{4}$$

$$\eta = h(p, \mu_r) \tag{5}$$

It is required that the transfer functions above have to be established to identify the parameter effects on system required torque and its variation. The transfer functions as in Equations (2) to (5) are identified through computer simulation combined with a regression analysis.

The entire CAE approach consists of two math models. At first, a kinematic model comprising sheet metal, glass, and seal is used to estimate the resultant forces at two carriers. The result is then used together with regulator properties in an analytical model to calculate the required torque.

The kinematic analysis is conducted using a commercial CAE solver ADAMS® [7, 8]. Glass movement is simulated with a quasi-static analysis. The forces at two carriers, f1 and f2, are calculated through this simulation. Close forms for transfer functions of f1 and f2 are established through a regression analysis. A quadratic response surface as in Equation (6) is used for the regression analysis. DOE (Design of Experiment) sampling process using Central Composite Design with 25 runs is conducted to construct the response surface [9, 10].

$$\begin{aligned} f(\delta_1, \delta_2, \mu_s, k) = C_0 + C_1 \delta_1 \\ + C_2 \delta_2 + C_3 \mu_s + C_4 k + C_5 \delta_1 \delta_2 \\ + C_5 \delta_1 \delta_2 \\ + C_6 \delta_1 \mu_s + C_7 \delta_1 k + C_8 \delta_2 \mu_s \\ + C_9 \delta_2 k \\ + C_{10} \mu_s k + C_{11} \delta_1^2 + C_{12} \delta_2^2 \\ + C_{13} \mu_s^2 + C_{14} k^2 \end{aligned} \tag{6}$$

where, C_0 .. C_{14} are coefficients to be determined by regression analysis.
Once Equations (3) and (4) are completed by regression analysis, Equations (2) and (5) can be obtained by an analytic approach.

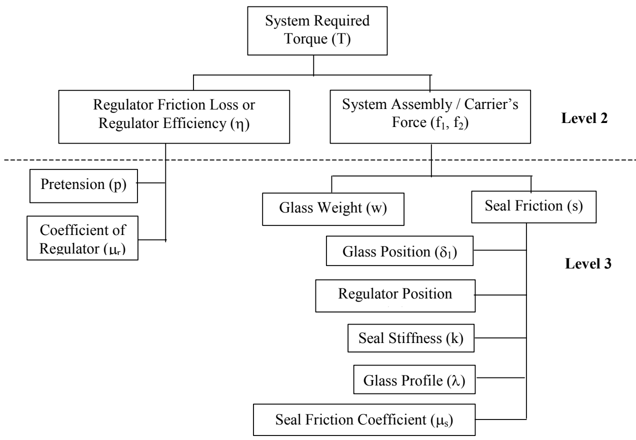

Figure 4. System Torque Hierarchy

4 Design Methodology

Two fundamental guidelines for the glass guidance design are 1) minimize variation of system load (DP1) and 2) select or design a motor with appropriate performance. From the set of transfer functions (2) to (5), the mean value of DP1 could be expressed in terms of mean values of design parameters (dp1, dp2, …, dpn) as

$$T = F(dp1, dp2, \ldots, dpn) \tag{7}$$

Using Taylor expansion, the transfer function for the variation of DP1 could be expressed in terms of mean values and variation (σdp1, σdp2, …, σdpn) of design parameters as

$$\sigma T = G(dp1, dp2, \ldots, dpn, \sigma dp1, \sigma dp2, \ldots, \sigma dpn) \tag{8}$$

By minimizing the variation of system load (σT) as an objective value with appropriate constraints for dpn and σdpn, a set of feasible design parameters and their associated variations for DP1 will be determined. Along the design process, all design parameters regarding the system load should have a variation smaller than the one derived from the minimization of Equation (8) to ensure the variation of system load smaller than the objective value.

In regard to the motor design/selection, two motor characteristics are needed to be determined – motor torque at a required RPM for glass movement and motor at stall. From Equation (7), the mean value of DP1 is determined. Based on the assumption of normal distribution, the probability density function for DP1 is determined and expressed in terms of random variable x. With a specified failure rate (α1) for the FR1, the probability density function (in terms of random variable y) of required motor torque at specified RPM can be determined based on the calculation of failure probability as

$$P(x < y) \leq \alpha 1 \tag{9}$$

Based on the assumption of normal distribution, the mean value and the ± 3σ band for the required motor torque at the specified motor RPM are determined.

The probability density function of FR2 is expressed in terms of random variable z. The random variable of system stall load z' is express as

$$z' = z - x \tag{10}$$

With a specified failure rate (α2) for the system stall load and two performance limits (Upper limit UL and Lower limit LL), the probability density function of random variable z is determined from the specified failure rate as

$$P(z' < LL \text{ or } UL < z') \leq \alpha 2 \qquad (11)$$

Based on the assumption of normal distribution, the mean value and ± 3σ band for the motor stall torque is determined.

By linearly connecting the two determined motor characteristic points for mean and ± 3σ values, the mean and design band for the motor performance are determined as the one shown in Figure 3. Along the design process, motor performance should always stay within the design band.

5 CONCLUSION

The cable-drive window regulator system has two simple functional requirements but lots of design parameters. Even though it is a decoupled system at the highest level, it is a highly coupled redundant design at the lowest design parameter level. This is mainly due to the other requirements for the door system such as seals and styling. This paper identifies the main focus area using the axiomatic design approach and proposes the procedure to establish the set of transfer functions using CAE simulation and regression method. From the transfer functions, the nominal value of system torque and its variation effect are easily predicted. This enables the engineer to synthesize the glass guidance system and choose the right motor.

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