

Analytical Study of a Dog Clutch in Automatic Transmission Application

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ABSTRACT

A dog clutch, if successfully implemented in an automatic transmission, provides better packaging and the potential for improved fuel economy. The technical requirements for this concept are examined through modeling and simulation. As a first step, a physics-based component level model is developed that provides an understanding of the basic contact and impact dynamics. The model is compared to a built-in AMESim block to establish confidence. This component level model is then integrated into a powertrain system model within the AMESim environment. As a test bed, the powertrain model is exercised to simulate a friction plate to dog clutch shift in a 6-speed automatic transmission. The analysis helps to define the slip speed target at the onset of the dog clutch engagement while ensuring shift requirements are met. Finally, the model is validated by comparing the simulated results with measured dynamometer data.

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INTRODUCTION

Friction clutches or brakes are commonly used in automatic transmissions during shifts. This approach can provide smooth clutch engagement and disengagement and good shift quality. However, efficiency losses occur during the energized mode because of slip or during de-energized mode due to the viscous drag between the friction plates. Further, multi-plate friction clutches consume considerable space and thus pose challenges when designing a compact transmission.

Driven by the demand for better fuel economy, the concept to replace friction clutches with dog clutches is worthwhile to be investigated. Compared to friction clutch, the dog clutch is more compact and provides lower drag losses. The dog clutch without a synchronizer has been applied in commercial and military vehicles [1-2]; however, very limited information on dog clutch modeling and simulation is available. Also, controlling a dog clutch during shifts (without synchronizers) has not been fully researched nor validated within integrated vehicles. Several papers discussed the manual transmission synchronizer modeling from the design perspective [3,4,5], but only a few papers have investigated the contact dynamics of synchronizers [6,7,8,9]. Most of this research focused on FEM analysis for multi-body dynamics systems, which has limited potential to be implemented into a transmission system model for drivability evaluation.

The major challenge associated with the dog clutch mathematical modeling is the requirement to capture the high frequency transients without sacrificing computational efficiency. These high frequencies result from the chamfer to chamfer contact in this application [10]. This research focuses

on developing a physics-based component level model that describes the contact and impact dynamics while maintaining computational accuracy and speed. The component model is implemented in a powertrain system model to evaluate the drivability of the automatic transmission designed with a dog clutch under different driving scenarios.

COMPONENT LEVEL DOG CLUTCH MODELING

To better understand the contact dynamics of dog clutch, a physics-based model is first developed at component level. Assuming one dog (designed as *g* for grounded) is completely grounded, the other dog (designated as *e* for engaging) with an initial rotating speed is actuated axially, as shown in [Figure 1](#). Similar to [7], the normal contact force F_{normal} between two dogs is represented by a contact stiffness K_{normal} and contact damping C_{normal} , where x_{normal} is the relative displacement and $\dot{x}_{normal}$ is the relative velocity along the normal direction.

$$F_{normal} = K_{normal}x_{normal} + C_{normal}\dot{x}_{normal} \quad (1)$$

Through kinematic analysis, the following relationships are determined:

$$x_{normal} = (\theta_g + (\theta_0 - \theta_x))R \cos \gamma \quad (2a)$$

$$\dot{x}_{normal} = (\dot{\theta}_g + (\dot{\theta}_0 - \dot{\theta}_x))R \cos \gamma \quad (2b)$$

$$\theta_0 - \theta_x = \frac{(x - x_0) \tan \gamma}{R}; \quad \dot{\theta}_0 - \dot{\theta}_x = \frac{\dot{x} \tan \gamma}{R} \quad (2c-d)$$

Here, θ_g is the angular displacement at the engaging dog, θ_0 is the index angle, and θ_x is the axial displacement dependent angle as shown in Figure 1. Also, R represents the pitch radius of dog teeth, γ is the chamfer angle, x_0 is the engaging dog axial travel from neutral to the first contact, and x is the engaging dog travel from neutral to an instantaneous contact position.

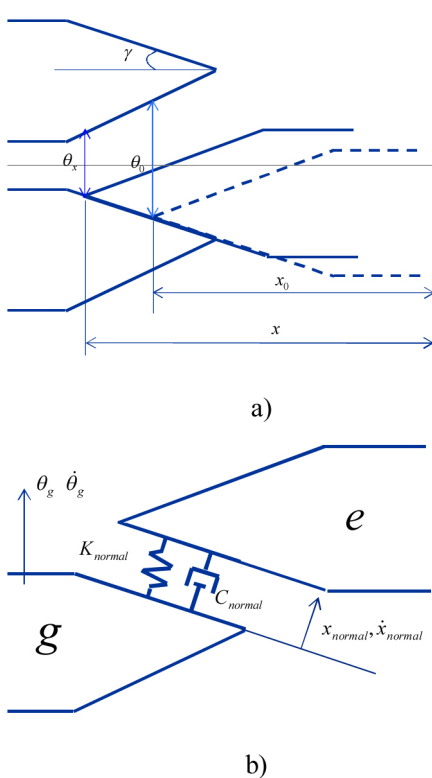


Figure 1. Dog-to-Dog Contact Dynamics Formulation

Further, vibro-impacts could occur due to the angular clearance between dogs. A translational analogy is illustrated in Figure 2a: along with relative motion in axial and rotational direction, impacts will occur in normal direction. Figure 2b describes the non-linear force-displacement relationship as in equation (3), where ε is the clearance.

$$F_{normal} = \begin{cases} K_{normal}(x_{normal} + \varepsilon) & \theta < -\varepsilon \\ 0 & -\varepsilon \leq \theta \leq \varepsilon \\ K_{normal}(x_{normal} - \varepsilon) & \varepsilon < \theta \end{cases} \quad (3)$$

Or, in a unified equation,

$$F_{normal} = K_{normal} \left(x_{normal} + \frac{1}{2} \left[(x_{normal} - \varepsilon) \operatorname{sgn}(x_{normal} - \varepsilon) - (x_{normal} + \varepsilon) \operatorname{sgn}(x_{normal} + \varepsilon) \right] \right) \quad (4)$$

To facilitate numerical computations, the signum function sgn can be further approximated by a hyperbolic tangent function ($\tanh$), with σ as a conditioning factor.

$$F_{normal} = K_{normal} \left(x_{normal} + \frac{1}{2} \left[(x_{normal} - \varepsilon) \tanh(\sigma(x_{normal} - \varepsilon)) - (x_{normal} + \varepsilon) \tanh(\sigma(x_{normal} + \varepsilon)) \right] \right) \quad (5)$$

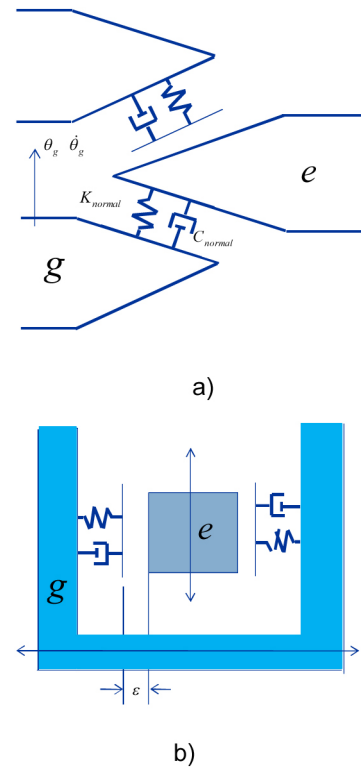


Figure 2. Translational Analogy of Vibro-impact Dynamics

It can be determined that the clearance varies with axial displacement because of the particular wedge-type geometry of the dog, as seen in Figure 1.

$$\varepsilon = \varepsilon_0 - (x - x_1) \tan \gamma \quad (6)$$

The normal contact force, together with the tangential friction force, is decomposed into axial and angular direction as follows, with μ as the friction coefficient.

$$F_{axial} = F_{normal} (\sin \gamma + \mu \operatorname{sgn}(\dot{x}) \cos \gamma) \quad (7a)$$

$$F_{tangential} = F_{normal} (\cos \gamma - \mu \operatorname{sgn}(\dot{x}) \sin \gamma) \quad (7b)$$

Now, the governing equations for the two-degree-of-freedom system can be generated. Assuming one dog is completely grounded, the engaging dog has dynamics in two directions.

Along the axial direction:

$$M\ddot{x} = F_e(t) - F_{axial} \quad (8)$$

where M is the mass of the engaging dog and $F_e(t)$ is the axial actuation force which can be time-varying or time-invariant.

Along rotational direction:

$$J_g \ddot{\theta}_g = T_g - F_{\tan} R \quad (9)$$

Here J_g is the moment of inertia and T_g is the external or inertial torque associated with the engaging dog. Based on the afore-derived physics, a Simulink model was developed as in Figure 3. The non-linear force displacement relationship of (5) can be modeled in the form of an embedded Matlab function. A conditioning factor σ of 10^6 is chosen to approximate the signum function.

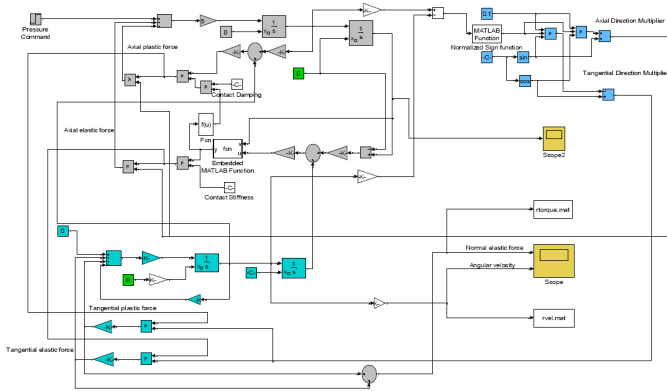


Figure 3. Physics-based Simulink Model

AMESim (Advanced Modeling Environment for Simulation of Engineering Systems) is commercial software and is widely used for one-dimensional multi-domain system simulation. A dog clutch component model has also been developed and included within the library. Unlike the force-balance approach that is used to develop the physics-based Simulink model, bond-graph theory is employed in AMESim to balance the input and output energy for each component. Figure 4 shows the AMESim model for dog clutch component level simulation. Both axial and angular direction dynamics are represented by a mass and moment of inertia respectively. Although the background computation is not known to users, AMESim provides a number of features, such as, friendly user interface.

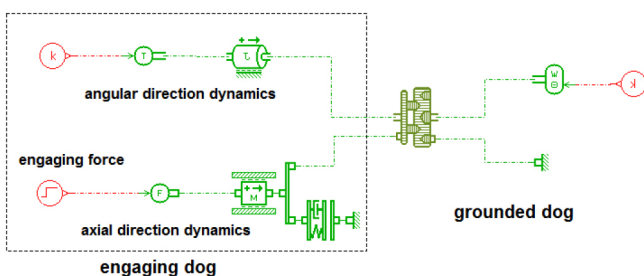


Figure 4. AMESim Model for Component Level Simulation

Figure 5 shows the comparison of Simulink and AMESim simulation results under two different conditions, one with zero initial relative speed and the other with nonzero initial relative speed. As shown, in both cases the impact torque and the rotational speed results match well in terms of torque magnitude and initial impact timing. While common parameters are used for both models, the computation algorithm of the AMESim is not an open source, and the actual numerical approach is likely different from the developed Simulink model, thus, minor differences are expected. Further, it is noted that the Simulink model is very dependent on the initial conditions to obtain a converged solution and AMESim model is more robust in handling the ill-conditioned numerical integration. In this study, the AMESim component level model will be used in future studies with a reasonable level of confidence. However, the Simulink model is still a significant exercise because it not only helps to understand the physics as an open source but also helps to build up the confidence level with AMESim model.

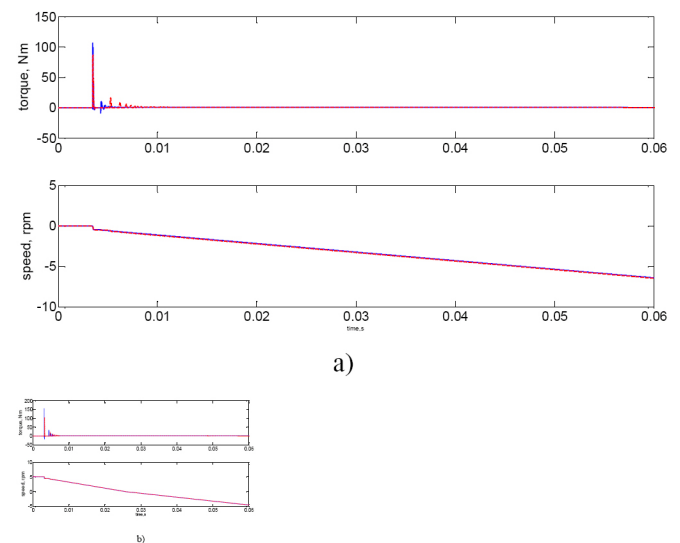


Figure 5. Comparison of Simulink and AMESim Simulation Results. a) Actuation force = 40 N, Initial Relative Speed = 0 rpm; b) Actuation force = 50 N, Initial Relative Speed = 5 rpm. Key: —, Simulink results; - -, AMESim results.

CLUTCH-TO-DOG SHIFT SIMULATION

The dog clutch component block is now implemented in the powertrain system model in AMESim, as shown in Figure 6. The dog clutch was modeled in accordance with the hardware design. A preloaded return spring is included for clutch release, and an elastic stop is included to limit the travel of the engaging dog along axial direction. Realistic pressure profiles for friction clutch and dog clutch are shown in Figure 7a. Although nothing unusual is found for friction clutch pressure profile, the pressure spikes caused by the impacts between dogs are observed, details illustrated in Figure 7b. These pressure spikes result from the impact of the engaging dog and the grounded dog; the high stiffness dog clutch impact will cause the clutch to bounce back. Accordingly, the hydraulic piston chamber gets compressed and generates high pressure spikes. However, because not all stiffness and