Modeling And Simulation For NVH Evaluation

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Abstract— **A new methodology based on modeling and simulation is proposed for Noise, Vibration, and Harshness (NVH) analysis for Anti-Lock Brake Systems (ABS). First, a correlation between NVH measurement data and simulation results need to be established. This relationship allows engineers to focus on modeling and simulation instead of NVH testing. The model can be set up to do different level of simulation and NVH analysis. If some data is available from actual testing, then the test data can be easily plugged into the model to replace the corresponding part in the model. It is especially useful when the design needs to be modified, or trade-off between ABS performance and NVH is necessary. The model can greatly reduce the time to market for ABS products. It also makes system level optimization possible.**

Index Terms— **Anti-Lock Brake Systems, Modeling and Simulation, Noise, Vibration, and Harshness, Vehicle Systems.**

I. Introduction

NVH is one of the important measures (see [2]) for many automotive systems such as Anti-Lock Brake Systems. It is estimated that the NVH related cost to the automotive industry is over one billion dollar every year. In order to improve NVH, one must be able to effectively evaluate NVH for a given system. This is a challenging task since most of the NVH evaluations are done in subjective manners (see [1]). Once an NVH evaluation method is chosen, the evaluation could be conducted many times as design changes are made during the entire product development process. This is a very time consuming and inefficient way of designing products.

CAE is widely used for NVH study. Many NVH simulators are available for automotive systems. However, the brake NVH modeling and simulation efforts are mostly limited to foundation brake (see [4-6, 9-12]). For ABS systems, NVH is still being studied and evaluated mainly by testing. Usually the focus in the early development stage is on the ABS performance (see [13, 14]). The NVH aspect is limited to simple theoretic analysis. After the desired performance is achieved, the engineers then try to improve NVH based on feedback from customers and test engineers. The vast majority of the NVH work for ABS systems is done in NVH labs or vehicles. More often than not, it is found that there are conflicting demands from ABS performance and NVH. Sometimes, the design process has to be repeated to have better NVH result. Not only the process is time consuming, costly, but also the result is neither reliable nor consistent.

In this paper we propose a new systematic approach for NVH study for ABS systems. First, extensive analysis should be done using existing test data. A good understanding of the relationship between system components and NVH needs to be established. Second, modeling and simulation should replace most of the actual testing or subjective evaluation. Third, NVH/performance optimization/trade-off must be done at the system level, not at the subsystem level.

The advantage of this new approach is clear: The end result is optimized for the overall system; The time it takes to complete the project is greatly reduced; The result is more consistent since the inconsistent human factor is taken out of the evaluation process; The cost is a fraction of current practice; This also allows advanced feasibility study before any hardware/test track is available for testing. We use ABS to illustrate the main ideas. However, the principal of the new approach can be applied to many other NVH related applications.

II. Modeling

A typical hydraulic schematic for ABS system is depicted in Fig. 1 (Only one wheel is shown). When the driver applies force to the pedal, the master cylinder pressure increases. This causes the wheel pressure to increase. If the wheel pressure exceeds the limit that is determined by the road surface friction coefficient, the wheel will be locked up. A locked-up wheel would not allow us to achieve optimal lateral and longitudinal forces to maintain vehicle stability, steerability and short stopping distance. Once the ABS algorithm detects this condition, the microprocessor would send a command to switch the isolation valve to the “closed” position. This prevents any brake fluid from flowing to the wheel. Next, the dump valve can be opened so that the brake fluid in the wheel can flow to the Low Pressure Accumulator (LPA). This completes a cycle for wheel pressure regulation. In the next cycle, the isolation valve is pulsed open to allow small amount of fluid to flow to the wheel. This starts the next pressure regulation cycle. The brake fluid dumped to the LPA needs to be pumped back to the master cylinder so that there is enough brake fluid for the next pressure regulation cycle. The pump is needed for another reason: once the LPA is full, then no wheel pressure regulation can be done (see [3]).

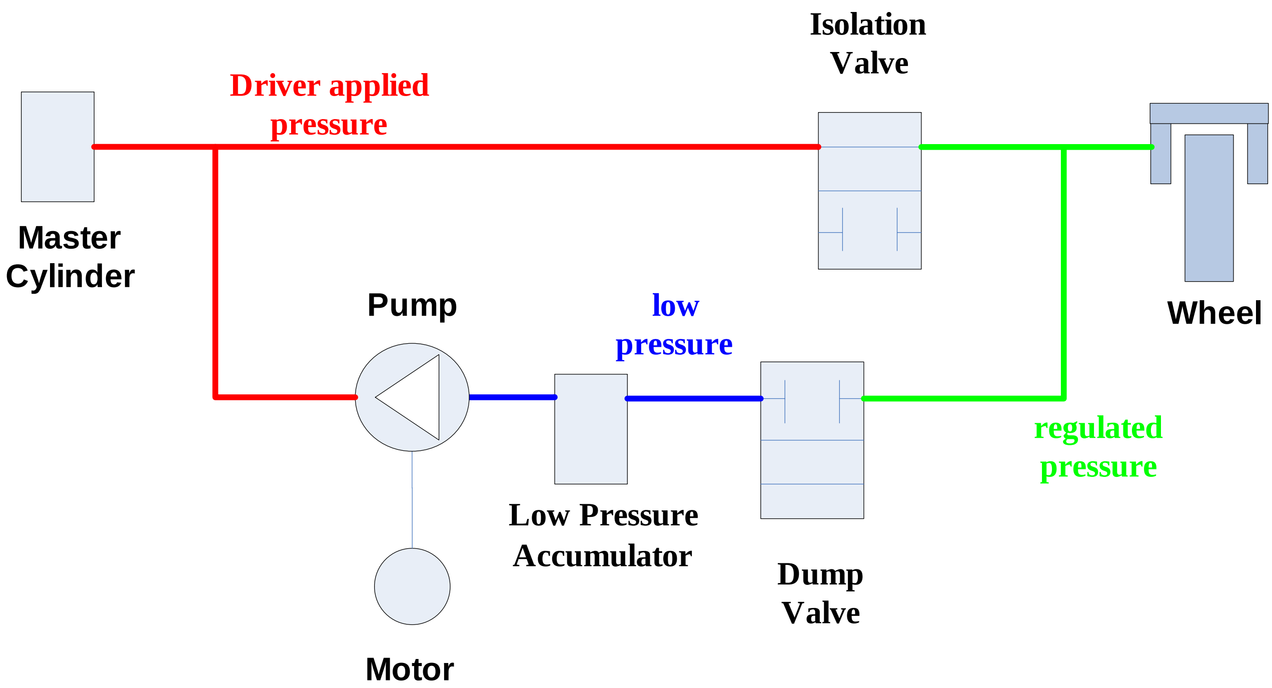

Fig. 1. A Typical ABS System

The noise is mostly caused by the "water hammering" effect when the valves are opened and closed and when the pump moves brake fluid back to master cylinder. The vibration of the brake pedal is mainly caused by the brake fluid movement due to the valve and pump activities. If there is more fluid flowing from master cylinder to the wheel than what is being pumped from LPA to master cylinder, then the driver will feel the pedal dropping. In the worst case, the pedal can drop all the way to the floor. On the other hand, when the pump delivers more fluid to master cylinder than the amount of brake fluid that flows to the wheel, then the driver will feel the pedal rising. During an ABS event, the pedal may move up and down constantly. The pedal vibration or "pedal feel", a terminology commonly used by test engineers, is a measure for the quality for this vibration.

First we study what elements of the ABS system affect NVH. Based on test data, the noise and vibration for ABS is affected by the following:

(a) MC characteristics
(b) Motor speed
(c) Hydraulic design for the ABS unit
(d) ABS control algorithm
(e) Location of the ABS unit
(f) Noise isolation capability
(g) Mounting of the ABS unit

Items (e) and (f) are usually determined by the OEMs. The other items are usually designed by brake suppliers. Let us first analyze the relationship between system components and NVH. Noise for ABS is mainly caused by the pressure pulsation in the master cylinder (MC). The MC pressure is determined by the driver input, i.e., applied pedal force, and the pump and isolation valves activities. The pump is driven by a DC permanent magnetic motor, which is in turn controlled by the ABS algorithm. The valves are also controlled by the ABS algorithm. The valve commands and the MC pressure determine the pressure at the wheels. The LPA can affect the wheel pressures in the sense that when it is full, the wheel pressure can not be reduced. When the LPA is not full, its impact on the wheel pressure is minimal. The MC pressure and LPA value determine the pump load, which directly affects the motor speed. The pedal vibration is determined by the MC pressure and the pump flow.

The system level model is shown in Fig. 2. Next we define each block in the system model. To make the equations easier to read, we use only one wheel, one pump, and one LPA in the model. The actual system of course has 4 wheels, 2 pumps and 2 LPAs.

Noise and Brake Pedal

A one time initial test is necessary to establish the relationship between NVH and some system parameters that can used for further simulation and analysis. This can usually be done using existing test data. During NVH test, many other variables are recorded. Because of the significant impact of master cylinder pressure has on NVH, the pressure trace is always recorded. We expect the fundamental structure of the relationship between the pressure, flowrate and NVH to be the same for different vehicle models. The only difference between different vehicle models will be the coefficients in the model.

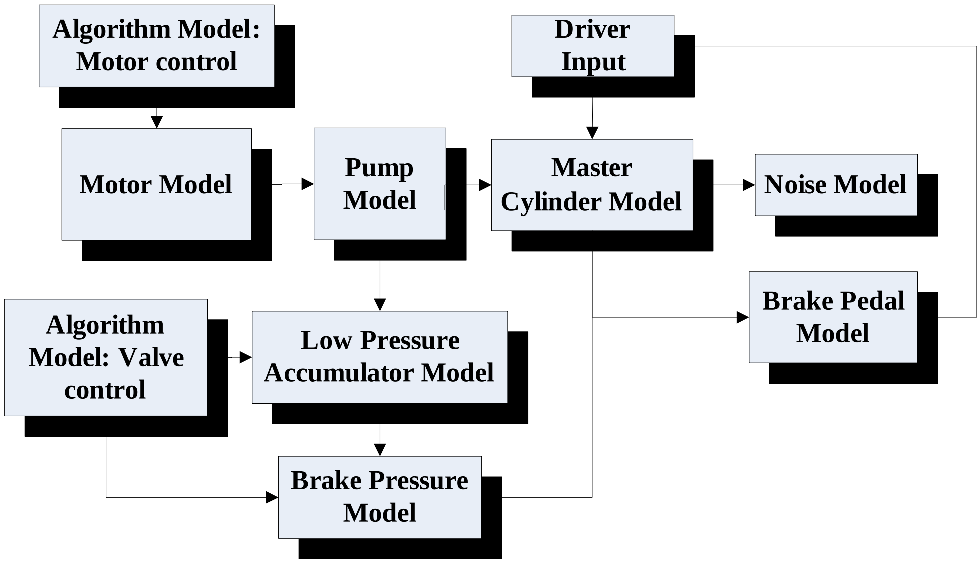

Fig. 2. System Model for NVH simulation

Therefore, once the fundamental structures of the noise and vibration models are established for one vehicle, we only need limited number of test traces to calibrate the noise and vibration model. This may seem to be as time consuming as the commonly used trial-and-error method. But the advantage of modeling and simulation for NVH evaluation is apparent when some part of the system design is modified. In this case, we only need to modify the model of the corresponding part and usually do not need to repeat all the NVH testing.

One of the main contributors to NVH is the pressure pulsation due to the pumping of the brake fluid from the LPA to MC driven by the motor. We propose to analyze test data to find the correlation between the magnitude and frequency of the pressure pulsation and the noise level. The relationship between the pedal vibration and hydraulic fluid movement can be modeled using the test data and curve-fitting as follows

$$N = f_1(P_{MC}, F) \quad (1)$$

$$\frac{dD_p(t)}{dt} = \frac{1}{\pi r^2}\left(F_o(t) - F_i(t)\right) \quad (2)$$

$$V_{pedal} = f_2(f_{pedal}, M_{pedal}) \quad (3)$$

where, P_{MC} is the master cylinder pressure; F is the frequency of the P_{MC} oscillation; D_p is the pedal displacement; r is the radius of the master cylinder bore; F_o is the pump output flowrate; F_i is the flowrate to the wheel; V_{pedal} is the measure of vibration of pedal; N is the noise measure; f_{pedal} is the frequency of the pedal displacement and M_{pedal} is the maximum pedal displacement.

Motor and Pump

Motor and pump can be modeled as follows

$$\begin{aligned}\frac{di_a(t)}{dt} &= \frac{1}{L_a}e_a(t) - \frac{R_a}{L_a}i_a(t) - \frac{1}{L_a}e_b(t)\\ T_m(t) &= K_i i_a(t)\\ e_b(t) &= K_b \frac{d\theta(t)}{dt}\\ \frac{d^2\theta(t)}{dt^2} &= \frac{1}{J}T_m(t) - \frac{1}{J}T_L(t)\end{aligned} \quad (4)$$

$$F_o(t) = EK\frac{d\theta(t)}{dt} \quad (5)$$

where $K_b = K_i$; K_i is the torque constant, in N-m/A; K_b is the back-emf constant, in V/rad/sec; $i_a(t)$ is the armature current, in A; R_a is the armature resistance, in Ω ; $e_b(t)$ is the back emf, in V; $T_L(t)$ is the load torque, in N-m; $T_m(t)$ is the motor torque, in N-m; $\theta(t)$ is the rotor displacement, in rad; L_a is the armature inductance, in H; $e_a(t)$ is the applied motor voltage, in V; J is the rotor inertia, in kg-m^2 ; K is the speed to flowrate gain; $F_o(t)$ is the pump output flow rate; and E is the pump efficiency.

Algorithm: Motor and Valve Control

The ABS algorithm calculates the commands for motor and valves in every algorithm loop, typically of 5 to 20 milliseconds. The command for the motor can be an on-off signal for the motor, which can be a result of some motor speed control algorithm. We can use the on-off command as an input or include the motor speed control algorithm in the model, in which case, the input would be a speed request. The commands for valves can be simply on or off. The command for motor is use by the motor model to control the motor speed. The commands for valves are used by LPA and Brake Pressure models to estimate pressure at the wheels and the volume in

LPA. These commands can be the input of the system model; it can also be the interface between this model and an external model such as ABS model that includes the ABS algorithm.

Low Pressure Accumulator

The volume in the LPA is determined by the fluid coming from the wheel and the fluid going to the pump. This can be modeled as

$$\frac{dV_{LPA}(t)}{dt} = F_o(t) - F_{bo}(t) \quad (6)$$

Where $V_{LPA}(t)$ is the brake fluid volume in LPA; $F_o(t)$ is defined in (5); and $F_{bo}(t)$ is defined in the brake pressure model in (10). During development testing, the LPA volume information is usually captured. In this case, the volume could be fed to the system model as an input.

Brake Pressure

The brake pressure can be determined using the valve commands and the brake PV curve.

$$P_b(t) = PV(V_b(t)) \quad (7)$$

$$V_b(t) = V_{bi}(t) - V_{bo}(t) \quad (8)$$

$$\frac{dV_{bi}(t)}{dt} = C\sqrt{P_{MC}(t) - P_b(t)}C_{appl}(t) \quad (9)$$

$$\frac{dV_{bo}(t)}{dt} = C\sqrt{P_b(t)}C_{dump}(t) \quad (10)$$

where PV is the brake PV curve; C is the flow coefficient for the isolation/dump valves; $V_{bi}(t)$ is the volume flow into the brake and $V_{bo}(t)$ is the flow out of the brake; $C_{appl}(t)$ and $C_{dump}(t)$ are the command for isolation and dump valves (they are digital signals equal to either 0 or 1). During development testing, the brake pressure is usually captured. In this case, the pressure calculation in (7) could be replaced as an input.

Master Cylinder

The master cylinder is the main pressure source during an ABS event. We can assume the drive applies a constant force, ramp apply, spike apply, or pedal pumping. The master cylinder model determines the pressure head that the pump is working against.

$$m\frac{d^2x(t)}{dt^2} = F_{pedal}(t) - \pi r^2 P_{MC}(t) \quad (11)$$

$$P_{MC}(t) = PV_{MC}(V_{MC}(t)) \quad (12)$$

$$V_{MC}(t) = V_i(t) - \pi r^2 x(t) \quad (13)$$

where P_{MC} is the MC pressure, $V_{MC}(\,)$ is the volume in MC; r is the MC piston bore radius; $x(t)$ is the MC piston displacement. The PV curve $PV_{MC}(t)$ of the master cylinder can be tested.

I. SIMULATION

The model developed in the previous section can be used in many different ways for NVH analysis for ABS systems.

Evaluate Impact of Motor Speed

Let's say two different traces of the motor speed are obtained from vehicle testing by a calibration engineer. Assuming other part of the system are the same, we can easily evaluate the NVH impact of the motor speed difference. In this case, we have no need to model the motor/control. Simply feed the motor speed to the pump input and the output is the NVH result.

Evaluate Impact of Pump Size and Efficiency

If the pump diameter or efficiency is changed during the design process, we can use the system model to recalibrate the motor speed controller. The NVH result can then be re-evaluated using the simulation tool.

Evaluate Impact of ABS Algorithm Calibration

We can use the system model to optimize the ABS algorithm calibration (optimize the control parameters). This includes the valve control and motor control too. Typically, an ABS algorithm goes through several rounds of calibration. We can use the model to come up with NVH results for different calibration sets. This would then allow us to do trade-off study between ABS performance and NVH.

Evaluate Impact of Master Cylinder Design

Some design parameters of the master cylinder can be varied to give a suggestion for the optimized values. During the product development process, it is not uncommon that the actual hardware is changed. The model can be used to give a quick estimation of what the impact would be.

In addition to the simulation that can be done using the system model proposed in this paper, we can further improve the simulation capability by including more components in the model. For example, the hardware durability is a very important aspect of ABS product. Only a few papers can be found (e.g. [7]) that address the performance issue together with durability and NVH. For ABS systems, durability is mainly determined by the temperature at the semiconductor switches and the current through the motor coil. The relationship is not straightforward. We propose to use test data to create an empirical model that uses motor current as input and durability performance as the output. Eventually the whole vehicle model can be added using software such as Carsim or Matlab. Then we can do virtual testing on the desk top for overall system evaluation including performance, NVH, and durability. This will be a very significant progress. We can also do hardware in the loop simulation ([8]). The advantage of these simulations is that we can design the test condition arbitrarily.

II. CONCLUSION

It is time consuming to try different combinations of hardware/software if we have to do NVH testing for each design. We propose a new method for NVH analysis using simulation. An ABS system is analyzed. A set of equations is derived. A simulation model can be built based on these equations. The purpose of the simulation method is to provide a first cut estimation of NVH results for ABS products. This method can be used in different ways, such as comparison of different controllers or trade-off study for ABS performance and NVH. We are still in the preliminary stage of developing this new method. A lot of work still needs to be done in order for this new approach to work. The effectiveness of this approach needs to be validated by a real system. We are also investigating the feasibility of extending this model to include the system durability analysis. If it works, we can perform system level optimization over ABS performance, cost, NVH, and durability.

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