CONCEPT STUDY OF ADAPTIVE SEATBELT LOAD LIMITER USING MAGNETORHEOLOGICAL FLUID

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ABSTRACT

Most current seatbelt load limiter technologies could only offer three or fewer predetermined patterns of seatbelt restraint force. However, researches have shown that, to better realize adaptive protection to different occupants under different crash severities, a continuously and real-time adjustable load limiter may be one step further. This concept could be especially favorable to vulnerable occupants such as small stature females and elderly people. Ideas have emerged suggesting possibility of using magnetorheological fluid (MRF) to realize such load limiter (MR-LL). This paper presents a concept study of MR-LL, aiming at evaluating its feasibility and establishing basic guidelines for prototype development. Configuration of an MR damper integrated with seatbelt retractor is selected in the study, in which the seatbelt force can be controlled by varying the strength of magnetic field exerted on the MRF inside the damper. The MR damper is numerically modeled and validated against experimental data found in the literature. Then by merging the MR damper model with a simplified occupant and seatbelt model subjected to sled impact loading, the performance of MR-LL under different parameter settings is studied and optimized. The simulation results demonstrate proof of the concept, indicating that the proposed MR-LL can generate various seatbelt force patterns with a wide adjusting range, thus to meet the requirement of both occupant adaptability and crash severity adaptability. Possible limitations of the proposed MR-LL are also discussed.

INTRODUCTION

Evolution from Load Limiting to Adaptive Restraint Force Control

When first introduced into market, seatbelt load limiter was initially adopted to prevent the seatbelt force from exceeding certain critical level in crash accidents, so as to reduce the risk of severe thorax compression and the corresponding injuries [1]. A typical design of load limiter has a deformable metal part integrated with the seatbelt retractor spool. The part will yield plastically when certain critical load is reached, so as to allow the previously locked seatbelt to be released out at a constant force level. Based on this mechanism, together with a seatbelt pretensioner, a constant force restraint (CFR) can be realized approximately. CFR has been identified to be the optimal pattern of restraint force when the occupant-vehicle system is considered as a simple single-DOF mass-spring-damper model [2]. Further analysis based on more complex models [2, 3] and other considerations (such as cooperating with airbag [4]) has identified other seatbelt force patterns such as CFR following an initial peak or the two-stage pattern to be more favorable than pure CFR(Figure1).

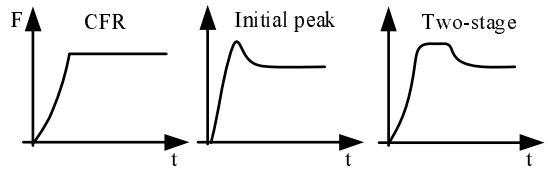

Figure 1. Different patterns of seatbelt force during crash.

Together with the research on restraint force optimization, more and more attention has been drawn to the concern about "adaptive restraint". The main focus is the influence of different occupant physical attributes, crash severity, and other factors on the restraint effectiveness. Researches have shown that if the parameters of the seatbelt force pattern such as load limiting level and the stage shifting time can be tailored according to the specific occupant and crash conditions, the protection result will be enhanced considerably [5, 6]. A widely cited example is the conclusion about the influence of age on the relation between thorax injury and the seatbelt load (Figure 2) [7, 8]. Because most restraint systems are designed based on 50th

percentile male occupant only, the concept of adaptive restraint is especially meaningful to other occupant categories such as small females and elderly people.

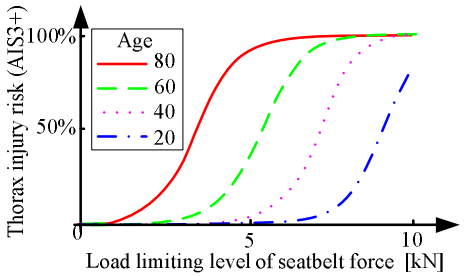

Figure 2. Age influence on thorax injury risk [8].

Beyond the above theories, some researchers have foretold a future form of restraint system, where the restraint force is controlled by a close-loop actuation system. During the crash, with the occupant motion as the feedback signal, the system can tune the seatbelt (and airbags) to compel the occupant tracking an optimal deceleration process, thus to minimize the injury for all kinds of occupants involved in various crash conditions [9] (Figure 3).

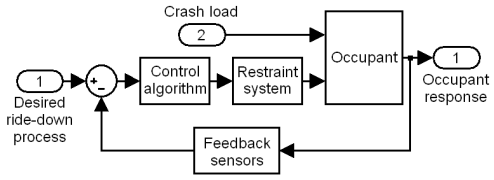

Figure 3. Future restraint system: close-loop control in crash real time.

Current Technology of Adaptive Load Limiter

Along with the evolution of restraint force theories, seatbelt load limiter has been widely used to realize the desired pattern of seatbelt force during crash. Despite the name "limiter", the role of seatbelt load limiter has been more and more considered to be beyond just limiting the maximum seatbelt force. Many designs of adaptive load limiter have been proposed in the literature to meet the desire of adaptive restraint force control proposed in the theories. Most of them provide "multi-level load limiting" with a "multi-deformable-part mechanism" [4, 10-13], which may be viewed as the upgrade of the traditional load limiter. By triggering the two or three deformable parts with different combination, this kind of load limiter could provide two or three predetermined levels of seatbelt force with CFR or multi-stage pattern (Figure 4).

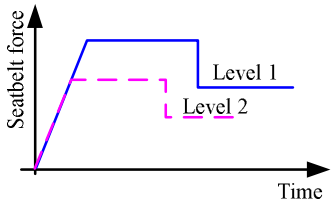

Figure 4. Multi-level load limiting.

This kind of mechanism is probably the only design of adaptive load limiter that has been maturely developed into real products. However, its limitations are also obvious. First, instead of adjusting the load limiting level steplessly, only two or three predetermined levels can be provided. Thus it cannot fully meet the optimal requirement of occupants with various physical attributes involved in various crash conditions. In addition, mechanism with deformable parts is not reusable. Moreover, this kind of load limiter has no potential of realizing continuously real-time control over seatbelt force, which renders it being insufficient for more advanced future restraint system mentioned earlier.

Advanced Adaptive Load Limiter and MR-LL

More advanced designs have been discussed in the literature with the aim of building a continuously and even real-time adjustable seatbelt load limiter. One of the proposals is controlling the seatbelt force during crash with the motorized seatbelt retractor (Figure 5a) [14]. Equipped with an electric motor to actuate the rotation of the retractor spool, the motorized seatbelt retractor has already been successfully used on seatbelt adjusting for wearing comfort and slack removing. However, considering the level of the seatbelt force and the short duration of action during the crash, the power needed for the motor to actuate the retractor spool during crash will be very considerable. This means the motor may have big size and high cost, which are highly undesirable for the retractor design.

Another idea under discussion is equipping the seatbelt retractor with a rotary brake (Figure 5b), which could control the resistant torque of the retractor spool, so as to control the seatbelt paying out and the corresponding restraint force during crash [15-18]. To meet the requirement of quick response and low power consumption, electro-mechanical brake with self-energizing mechanism is favorable. In 2007, Siemens VDO (Continental) announced the development of such a product based on its "Wedge Brake" technology [19]. However, no available product has been demonstrated yet.

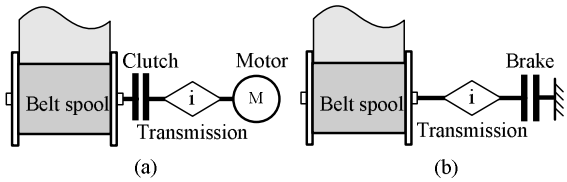

Figure 5. Retractor equipped with motor (a) or brake (b).

Besides the above two proposals, a new idea emerged in the recent years suggests the possibility of building adaptive load limiter with magnetorheological fluid (MRF). As a kind of the so-called "smart fluid", MRF is a suspension of magnetic polarizable micro-particles in a carrier fluid. When subjected to magnetic field, the fluid greatly increases its apparent viscosity, and develops a yield stress which monotonically increases with the strength of the applied magnetic field (Figure 6). The transmission is fully reversible and almost instantaneous. This rheological character is very favorable for developing simple, quiet, rapid-response interfaces between electronic controls and mechanical systems [20].

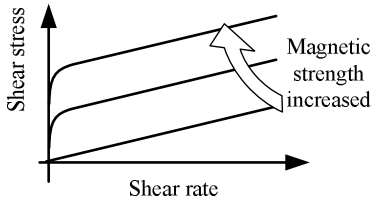

Figure 6. Rheological character of MRF.

Many researches have been carried out to study the application of MRF on various areas such as vibration damping, rotary brake, human prosthetics, and optical polishing. In the recent years, several patents [21-24] have proposed the idea about MR load limiter (MR-LL), which equips the seatbelt retractor spool with a piston damper or a rotary brake built with MRF. These designs could enable the seatbelt force to be controlled by varying the magnetic field applied on the MRF inside the damper or bake. Considering the rheological feature of MRF, this kind of mechanism may have the potential of realizing a continuously and real-time adjustable seatbelt load limiter.

Moreover, unlike load limiter which adopts electro-mechanical mechanism like the motorized retractor or electro-mechanical brake, MR-LL does not need motor and has relatively fewer moving parts, which ensures reduction of the device complexity. In addition, considering the advance of manufacturing technology which has considerably reduced the cost of MRF, MR-LL may have much lower cost compared to other designs.

However, despite its seemingly promising outlook described in the patents, no substantial study has yet been published to discuss the feasibility of MR-LL and the corresponding design principles. In the following sections, this paper presents a concept study of MR-LL, aiming at evaluating its feasibility and establishing basic guidelines for prototype development.

CONFIGURATION OF MR-LL

Comparison between Possible Configurations

Generally, MRF inside MR devices works in one of the three basic operation modes [20]. As illustrated in Figure 7, the three modes are different from each other by the driving force and the moving direction of the boundary. Among the three modes, except the squeeze mode, which is usually used only at controlling millimeter-order movements, the other two modes could both be used to build MR-LL.

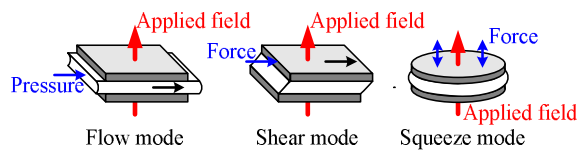

Figure 7. Three basic operation modes of MRF.

Based on the flow mode, a piston damper can be built and linked to the seatbelt retractor spool directly or via mechanical transmission (Figure 8). The resistant force is generated by the damper when the seatbelt is pulled by the occupant during crash.

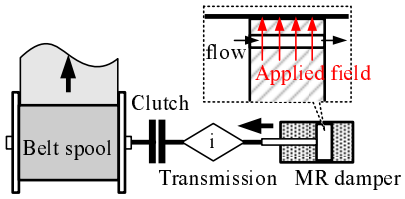

Figure 8. Retractor with MR damper.

Based on the shear mode, an MR rotary disk brake is linked to the retractor spool (Figure 9). When the MRF filled in the gap between the brake disk and the shell becomes more viscous as the result of the applied magnetic field, the brake could generate resistant torque due to the shear force of the MRF caused by the relative motion between the brake disk and the shell.

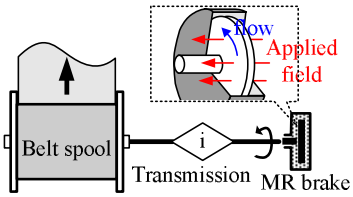

Figure 9. Retractor with MR brake.

By varying the strength of magnetic field spread across the orifice of the MR damper or the cavity of the MR brake, the apparent viscosity of MRF can be controlled, and thus the resistance force of the damper or the torque of the brake can be adjusted.

Although both have been proposed in the patents, a quick comparison shows that MR damper is more suitable for MR-LL configuration. Consider the size of MR device to generate enough seatbelt resistant force during crash: It has been reported that MR piston damper with an outer diameter about 40mm is capable of generating 3~6kN peak resistant force under 3m/s impact loading speed [25, 26], which is close to the energy absorbing intensity of seatbelt load limiter during vehicle crash. Further, if assume the transmission ratio between the piston motion and the belt paying out to be 1, then the stroke of the MR damper piston will be equal to the paying out of the seatbelt from the load limiter during crash, which is approximately at 100mm level. The above estimation indicates that the size of MR damper needed to generate enough seatbelt resistant force during crash could be acceptable for vehicle onboard installation.

On the other hand, there have been reports stating that under the current technique, an MR rotary disk brake with a size up to 100mm in diameter and 40mm in length could only generate resistant torque no more than 4Nm [27, 28]. Thus to meet the approximately 80Nm torque needed for the load limiting operation, a gear set with a transmission ratio up to 20 is needed. Besides the increase of system complexity, size and cost it brings, such a large transmission ratio will also significantly increase the dynamic inertia of the moving parts, and thus add difficulty to device controlling.

MR-LL using MR Damper

Based on the above analysis, it can be seen that MR damper is more suitable than MR brake for MR-LL application. Generally, MR-LL using MR damper involves an MR piston damper linked to the seatbelt retractor spool via certain transmission. Figure 10 demonstrates one of the typical designs where a screw transmission is adopted.

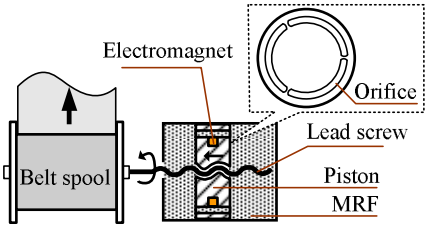

Figure 10. One of the typical designs of MR-LL using MR damper.

When the MRF is forced to flow through the circular orifice on the piston by piston sliding, resistant force will be generated mainly by the pressure difference between two sides of the piston. Magnetic field is generated transversely along the orifice by electromagnet, controlling the apparent viscosity of MRF and the corresponding damping force.

SIMULATION PLATFORM OF MR-LL

In order to identify, optimize and determine appropriate design parameters of the proposed MR-LL, a simulation platform is built. As for the modeling environment, although finite element simulation is very popular for fluid motion modeling, it is not very convenient for simulating continuously real-time controlled rheological behavior, and is also difficult to be linked to control theory analysis software. Because of these considerations, MATLAB/Simulink is widely preferred by various studies, including this one, for the modeling of systems engaging MR devices.

MR-LL Modeling

Under the proposed MR-LL configuration, the loading force and the paying out velocity of the seatbelt will be proportional to those of the MR damper, with the scale equaling to the transmission ratio i between the seatbelt paying out and the damper piston sliding. Thus the modeling of MR-LL is mainly the modeling of MR damper.

Considering the width of the circular orifice on the piston ($2h$), which is much smaller than the length (L) and the central circle radius of the orifice (R_o), the flow field of MRF through the orifice could be simplified as one-dimensional and central symmetrical (Figure 11) [29-31].

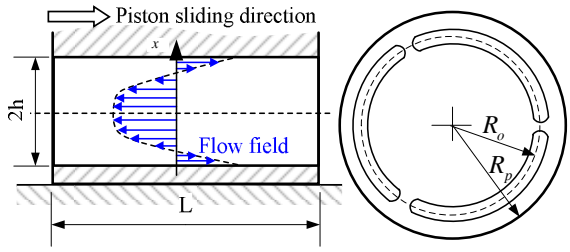

Figure 11. The flow field of MRF through the orifice.

The modified Herschel-Bulkley model [30] is adopted to describe the constitutive property (Figure 12) of the MRF, and the shear stress τ of MRF is given by the following constitutive equation:

$$\tau(x,t) = \left(\frac{\tau_{yd}}{\left|\frac{\partial u(x,t)}{\partial x}\right|^n + \varepsilon} + \eta\right)\cdot\left(\frac{\partial u(x,t)}{\partial x}\right)^n \quad (1).$$

where yield stress τ_{yd} is determined by the average strength of the applied magnetic field H, which is proportional to the current of the electromagnet $H = \alpha I$. Parameter ε is used to describe the pre-yield behavior, and η is the post-yield viscosity. Parameter n is used to describe the shear thinning behavior at high shear rate, which is believed to be necessary when studying damper subjected to impact load [31]. All the parameters and the relation between τ_{yd} and H can be obtained based on the test data provided by the MRF manufacturer.

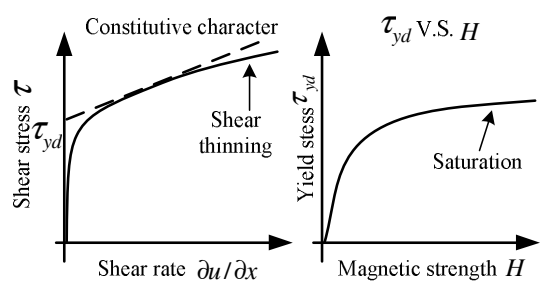

Figure 12. Constitutive property of MRF.

Besides the constitutive equation, other governing equations are listed as follows:

Equation of fluid motion:

$$\rho\frac{\partial u(x,t)}{\partial t} = -\frac{\Delta P(t)}{L} + \frac{\partial \tau(x,t)}{\partial x} \quad (2).$$

where ΔP is the pressure difference between two sides of the piston, and ρ is the fluid density.

Flow boundary condition:

$$u(0,t) = u(2h,t) = v_p(t) \quad (3).$$

where v_p is the moving speed of the piston.

Equation of continuity:

$$v_p(t)\cdot A_p = -\int_0^{2h} u(x,t)\cdot dA_o \quad (4).$$

where A_p is the top (and bottom) area of the piston, and A_o is the cross-sectional area of the orifice.

Equation of piston motion:

$$F_d(t) - F_\tau(t) - F_{press.}(t) = m_p\frac{dv_p(t)}{dt} \quad (5).$$

where F_d is the loading force of the damper. F_τ is the shear force caused by the MRF shear stress distributed across the orifice side surface. $F_{press.} = \Delta P\cdot A_p$ is the force caused by the pressure difference between two sides of the piston.

The governing equations are solved with the ODE solver of MATLAB/Simulink. In order to use the ODE solver of Simulink, which is designed to solve time-continuous problems rather than space-continuous problems, a "semi-discrete" method has to be adopted [32]. The method divides the flow field along the x direction into many divisions ($2N$) of equal width, replaces the space distributed variable with discrete vector, and the space differential term with difference quotient:

$$\begin{cases} u(t,x) \to \mathbf{U}(t) = \left[u_1(t), u_2(t), \cdots, u_N(t)\right]^T \\ \tau(t,x) \to \mathbf{T}(t) = \left[\tau_1(t), \tau_2(t), \cdots, \tau_{N+1}(t)\right]^T \\ \frac{\partial u}{\partial x} \to \frac{\partial \mathbf{U}}{\partial x} = \left[\frac{u_i - u_{i-1}}{\Delta x}\right]_{i=1\sim N+1} \begin{pmatrix} u_0 = v_p \\ u_{N+1} = u_N \end{pmatrix} \\ \frac{\partial \tau}{\partial x} \to \frac{\partial \mathbf{T}}{\partial x} = \left[\frac{\tau_i - \tau_{i-1}}{\Delta x}\right]_{i=2\sim N+1} \end{cases} \quad (6).$$

(Spatial symmetry of the flow field is considered. Subscript 1 marks the boundary of the orifice, and N marks the center.)

The difference quotient can be operated in Simulink using the "selector" module illustrated in Figure 13.

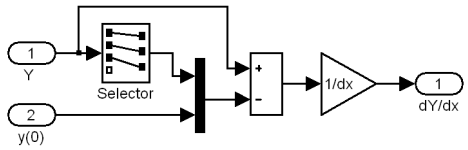

Figure 13. Operation of difference quotient under Simulink [32].

Based on this method, the governing equations can be rewritten as:

$$\mathbf{T} = \left(\frac{\tau_{yd}}{\left|\frac{\partial \mathbf{U}}{\partial x}\right|^n + \varepsilon} + \eta\right) \cdot \left(\frac{\partial \mathbf{U}}{\partial x}\right)^n \quad (7).$$

$$\rho \frac{\partial \mathbf{U}}{\partial t} = -\frac{\Delta P}{L} + \frac{\partial \mathbf{T}}{\partial x} \quad \left(u_1 = v_p \ , \ \tau_{N+1} = 0\right) \quad (8).$$

$$v_p A_p = -2\sum_1^N u_i dA_o \quad (9).$$

$$F_d - F_\tau - \Delta P \cdot A_p = m_p \frac{dv_p}{dt} \quad (10).$$

Before solving the above equations in Simulink, some additional transformations are made in order to prevent the appearance of algebraic loop, which will significantly slow down the solving process:

Eq. (8) $\rightarrow$ $$\rho \sum_1^N \frac{\partial u_i}{\partial t} \Delta x = -\frac{\Delta P}{L} h + \sum_1^N \frac{\partial \tau_i}{\partial x} \Delta x \quad (11).$$

Eq. (9) $\rightarrow$ $$\frac{dv_p}{dt} A_p = -2\sum_1^N \frac{\partial u_i}{\partial t} dA_o \quad (12).$$

Eqs. (11) and (12) $\rightarrow$

$$\frac{dv_p}{dt} \frac{A_p \rho}{4\pi R_o} = \frac{\Delta P}{L} h - \left(\tau_{N+1} - \tau_1\right) \quad (13).$$

Eqs. (10) and (13) $\rightarrow$

$$\frac{A_p \rho}{4\pi R_o m_p} F_d = \Delta P \left(\frac{A_p^2 \rho}{4\pi R_o m_p} + \frac{h}{L}\right) + \tau_1 \left(\frac{A_p \rho L}{m_p} + 1\right) \quad (14).$$

Most modules in Simulink support vector parameters, Eqs. (7) (8) (9) and (14) can be linked in Simulink with the configuration shown in Figure 14.

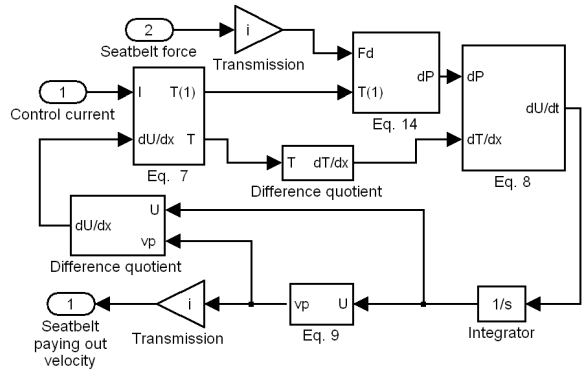

Figure 14. Model configuration of MR-LL.

The seatbelt force and the control current of the electromagnet (proportional to the magnetic field strength) are set as the input variables, and the seatbelt paying out velocity is set as the output variable.

Validation of the MR-LL Model

The model of MR-LL is validated by comparing the dynamic character of its main part, the model of MR damper, against the test data found in literature [20, 26, 33]. Two types of load have been studied: steady load and impact load. Under the steady load, a constant loading force is applied and the piston moves at a constant velocity. Under the impact load, the damper is subjected to a drop tower test. The parameters of the damper structure, the MRF properties and the loading condition are set according to the data in the literature. Figures 15 and 16 show the comparison between the simulation and the actual test results, good correlations can be seen.

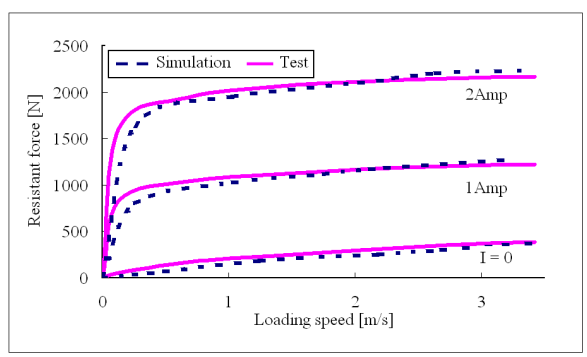

Figure 15. MR-LL model validation - steady load.

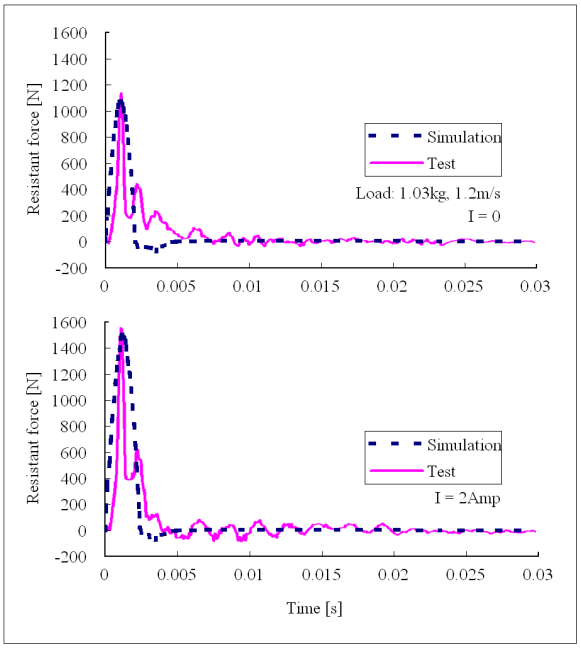

Figure 16. MR-LL model validation - impact load.

Occupant and MR-LL Seatbelt System Modeling

An "occupant and MR-LL seatbelt system" model subjected to sled impact load is further established, in which the MR damper model is part of it. This model will serve as the simulation platform for the parametric study of MR-LL in the next section.

A simplified three-body, two-dimensional dynamic model of occupant is adopted (Figure 17). Although not as sophisticated as more complex occupant models like those available in MADYMO software tool, such a model has been proved to be capable of providing good representation of the actual system response, and has been frequently used to provide better understanding of the dynamics and interaction of the occupant and restraint system [34]. Simulating the model is highly time-efficient, thus it is very suitable for parametric study, in which many iterations are required. Due to this merit, this kind of model has been recommended for concept study of adaptive restraint devices [35], while the more sophisticated MADYMO occupant models will be preferably used in further design and analysis following the concept phase.

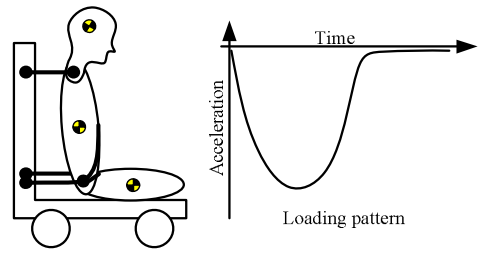

Figure 17. Three-body, two-dimensional occupant model.

The occupant model is built using the Simmechanics package of Simulink. The dimensional and inertial parameters of the occupant body, the viscoelastic property of the seatbelt, and the sled impact loading pattern are set using the data from the studies by Paulitz et al. in 2005 and 2006 [34, 35], in which a three-body, two-dimensional 50th percentile ATD model is used to simulate the actual process of a standard 56 km/h frontal impact test conducted by NHTSA.

The sled model is linked to the MR-LL model in Simulink with the configuration shown in Figure 18. This combined model of "occupant and MR-LL seatbelt system" is used to simulate the performance of MR-LL under given MR-LL control current pattern during crash.

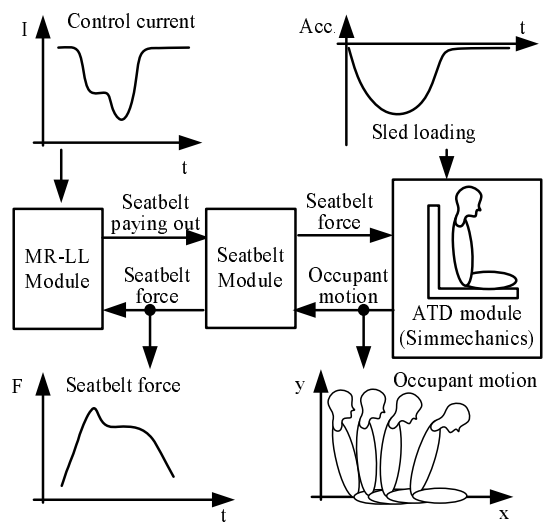

Figure 18. Model configuration of "occupant and MR-LL seatbelt system".

PARAMETRIC STUDY AND OPTIMIZATION OF MR-LL STRUCTURE

The objective of parametric study is to find the influence of each main design parameter on the performance of MR-LL, so as to establish the basic

guidelines for design. In addition, the optimized settings of the parameters and the corresponding MR-LL performance can be used to evaluate the proposed concept.

Evaluation Indices

Adaptive load limiter is supposed to provide restraint force with a suitable and widely adjustable range, so as to be capable of offering tailored protection to occupants from teenager to elderly, from small stature to large stature, and to impact from low speed to high speed. Based on this aim, two indices are defined to evaluate the performance of MR-LL:

$$\begin{cases} \Delta F = F_{p-\max} - F_{p-\min} \\ \overline{F} = \dfrac{F_{p-\max} + F_{p-\min}}{2} \end{cases} \quad (16).$$

where $F_{p-\max}$ is the peak seatbelt force during crash when the magnetic field is always applied with the maximum strength (the saturation limit of the MRF), and $F_{p-\min}$ is the peak seatbelt force during crash when no magnetic field is applied at all (Figure 19).

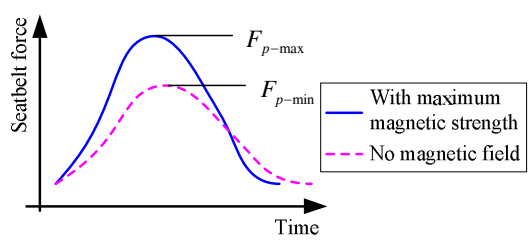

Figure 19. Definition of $F_{p-\max}$ and $F_{p-\min}$.

To a large extent, ΔF and $\overline{F}$ can represent the adjusting range of the seatbelt force controlled by MR-LL, and can be acquired easily from simulation runs. Thus it is reasonable to choose them as the evaluation indices of the parametric study.

Parametric Study and Optimization

The performance of the proposed MR-LL under different settings of parameters is evaluated by the indices ΔF and $\overline{F}$ defined in Eq. (16). The concerned variables and their initial settings are listed as follows (also see Figure 11):

- Type of MRF – "MRF-122" by LORD Corp.
- Radius of the piston $R_p = 20.5$mm
- Mass of the piston $M_p = 200$g
- Central circle radius of the circular orifice $R_o = 15$mm
- Width of the orifice $2h = 1$mm
- Length of the orifice $L = 20$mm
- Transmission ratio between the seatbelt paying out and the piston sliding $i = 1$

Fractional parametric study is conducted, where only one parameter is varied at a time while the others remain at their initial settings. Figure 20 shows the corresponding changes of the MR-LL performance.

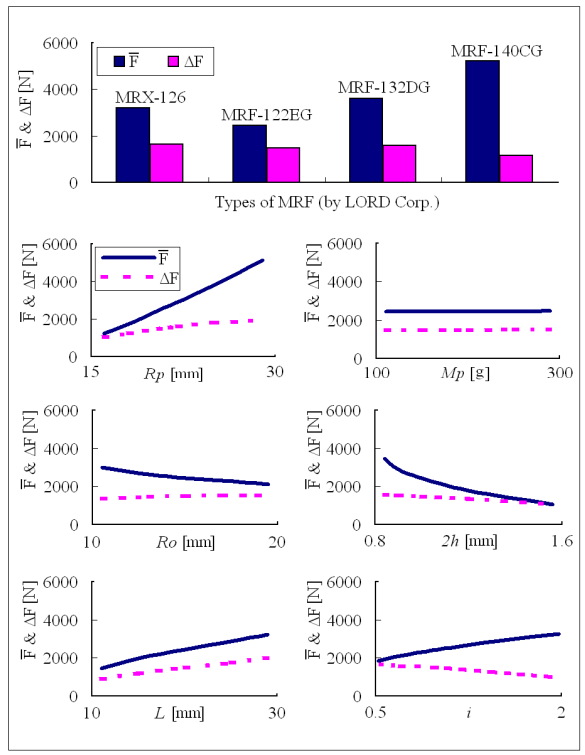

Figure 20. The influence of MR-LL parameters.

Although cannot show the interaction between variables as a full parametric study can do, these fractional studies are efficient at revealing the general influence trend of each parameter on the performance of MR-LL. As shown in Figure 20, different parameters have different features of influence. Some parameters such as R_o and h have significant influence on $\overline{F}$, but do not have much effect on ΔF. While some others such as the type of MRF, R_p, L and i can only change both indices together. In the process of performance optimization, the parameters of the second kind are first tuned within the reasonable range to enlarge ΔF, while the ones of the first kind are tuned next to obtain a suitable $\overline{F}$. Following this routine, a set of optimized parameters is acquired and listed in Table 1, with the final evaluation indices as $\Delta F = 3092N$ and $\overline{F} = 4156N$.

Table 1.
Optimized settings of MR-LL parameters

Design variable	Setting
Type of MRF	MRF-132DG
Radius of the piston [mm]	23
Mass of the piston [g]	200
Central circle radius of the circular orifice [mm]	20
Width of the orifice [mm]	1
Length of the orifice [mm]	30
Transmission ratio between the seatbelt paying out and the piston sliding	2

ADAPTABILITY OF THE PROPOSED MR-LL

Based on the optimized parameters obtained, the crash severity adaptability and occupant adaptability of the proposed MR-LL are examined using the simulation platform. To examine the crash severity adaptability, several different crash speeds are applied. While to examine the occupant adaptability, the physical parameters of the occupant model are varied from the initial 50th percentile male setting to 5th percentile female and 95th percentile male settings. The MR-LL is controlled to provide basic constant force pattern. Different levels of constant force are assumed to serve different crash cases. Figures 21 and 22 show the resulting patterns of the seatbelt force and the corresponding control current of the electromagnet (the ratio between the average magnetic strength and the control current is assumed to be 100 [kAmp/m]/[Amp]).

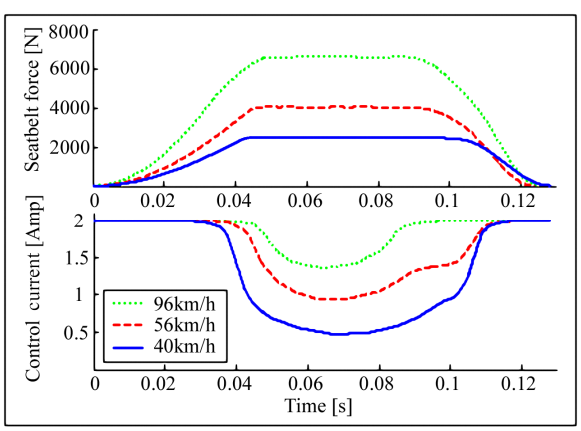

Figure 21. Crash speed adaptability (50th ATD).

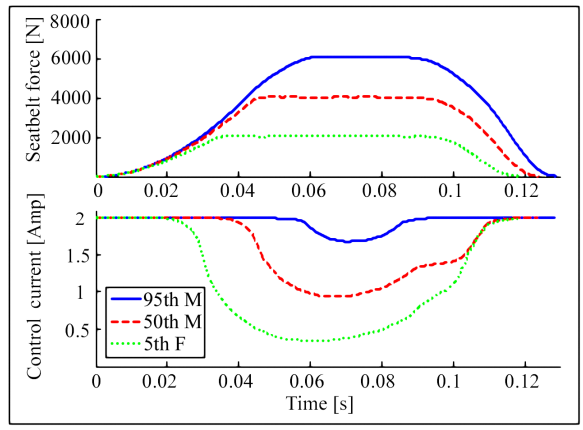

Figure 22. Occupant adaptability (56km/h).

Besides the basic constant force pattern, the simulation result also demonstrates the capability of the proposed MR-LL to generate other possibly desired patterns of seatbelt force as demonstrated in Figure 23.

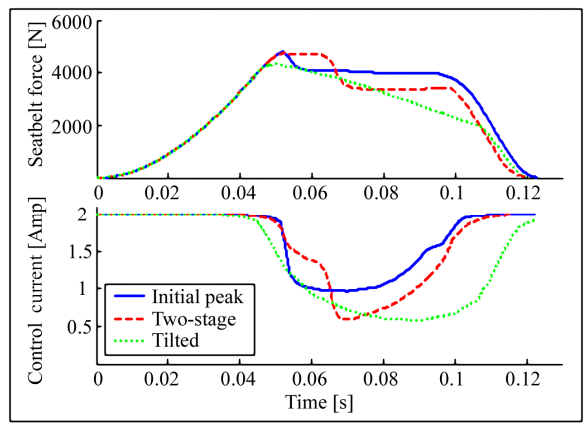

Figure 23. Generating different patterns of seatbelt force.

As demonstrated above, the simulation result indicates that the proposed MR-LL has strong potential to provide continuously and real-time adjustable control over the seatbelt force, thus possess good adaptability to different occupants under different crash severities.

CONCLUSIONS

Magnetorheological fluid has been suggested to have the potential of being used to build adaptive seatbelt load limiter, which could provide continuously and real-time adjustable control to seatbelt force during vehicle crash. This kind of function has been identified to be quite necessary to the protection of occupants with various physical attributes involved in different crash severities. In order to study the feasibility of the proposal, a concept study has been

carried out and documented in this paper. First, the structure that has an MR damper integrated with seatbelt retractor is identified as the most promising configuration for MR-LL. Then, based on a simulation platform, parametric study and performance optimization have been conducted. The simulation result using the optimized parameters indicates good adaptability of the proposed MR-LL. Depending on the need of protection to occupant with different statures involved in different crash speeds, the optimized MR-LL can generate various patterns of seatbelt force with a wide adjusting range.

On the other hand, despite the proved concept, there are still some possible limitations of the proposed MR-LL. One concern is the device size. Although the size-related parameters are constrained within reasonable range in the performance optimization, the resulting size of MR-LL is bigger than traditional load limiters. If a 200mm maximum paying out of seatbelt is assumed, the size of MR-LL can be approximately estimated to be 50mm of diameter and 150mm of length. This might pose a problem for vehicle onboard installation. Other concerns include the sealing of MR damper and the depositing of MRF. Although mature solutions have been claimed by MRF manufacturers, the impact of these factors on the device durability of MR-LL is still uncertain.

To examine the above considerations, a physical prototype is desired. The work documented in this paper is the first phase of MR-LL development. Under the guidelines obtained in this concept study, the next steps include further analysis of the system, detailed components design, magnetic circuit analysis, and the electric power source development. Moreover, the simulation platform presented in this paper could also benefit the study of the close-loop control algorithms for the future adaptive restraint systems.

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