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Compliant Link Suspension

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ABSTRACT

This paper discusses a compliant link suspension concept developed for use on a high performance automobile. This suspension uses compliant or flexible members to integrate energy storage and kinematic guidance functions. The goal of the design was to achieve similar elasto-kinematic performance compared to a benchmark OEM suspension, while employing fewer components and having reduced mass and complexity, and potentially providing packaging advantages. The proposed suspension system replaces a control arm in the existing suspension with a ternary supported compliant link that stores energy in bending during suspension vertical motion. The design was refined iteratively by using a computational model to simulate the elasto-kinematic performance as the dimensions and attachment point locations of the compliant link were varied, until the predicted performance closely matched the performance of the benchmark suspension. A mock-up of the proposed compliant link suspension was built together with an adjustable test fixture, and experiments were carried out to validate the results from simulations. The new suspension is less complex and weighs less than the original suspension without sacrificing basic elasto-kinematic performance.

INTRODUCTION

Vehicle suspensions typically use rigid links to provide kinematic guidance to the wheel, and springs and dampers to store and dissipate energy during wheel motions. The goal of this work was to design a suspension system that functionally integrates the tasks of kinematic guidance and energy storage by utilizing compliant or flexible links within the suspension, with little or no compromise in suspension performance. In utilizing a compliant link suspension we expect a reduction in weight, part count, and ultimately reduced production costs.

The concept of using compliant members in suspensions was derived from general compliant mechanisms which carry out motion transfer or transformation of energy and at the same time act as an energy storage mechanism [1]. This paper concentrates on the design and evaluation of a rear suspension for a high performance vehicle that utilizes compliant members for both wheel guidance and energy storage.

Traditional and existing suspensions incorporate compliance in the form of bushings, and springs (coil and leaf) [2]. The basic type of compliant suspension is the longitudinal leaf spring found on many light trucks in production today [3]. The leaf spring stores energy and provides wheel guidance by flexing the leaves. These leaf springs are usually stacked with progressively shorter leafs, which are made of steel. Research has shown that the use of composite leaf springs would provide reduced weight and increased durability compared to steel [4, 5].

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This paper describes the development of a variant design utilizing compliant links to replace an existing OEM suspension. The stock OEM layout utilizes a longitudinal rigid link, which houses the wheel carrier, and two lateral arms connecting the wheel carrier and the chassis for wheel guidance. Our variant design replaces the upper lateral link with a ternary supported compliant link. The reference OEM suspension was first simulated in ADAMS, and the results were compared to data from kinematics and compliance testing to insure model fidelity. Following this, the compliant suspension was modeled in ADAMS. The compliant links were designed in ANSYS and a reduced modal description of their characteristics was exported to ADAMS. This model was used for iterative design of the compliant member to most closely duplicate the elasto-kinematic performance of the reference suspension. Finally, an adjustable test fixture was built to conduct experiments on a mock-up of the compliant suspension. The test fixture utilized all of the original components of the OEM suspension with the exception of the upper lateral link, which was replaced by an aftermarket composite leaf spring supported at three points, i.e. ternary support. Additional hardware was fabricated to attach and support the composite spring at both ends and at the middle. Test results obtained from the mock-up were used to validate the results from simulations of the compliant suspension model in ADAMS.

COMPLIANT SUSPENSION DESIGN CONCEPT

The notion of using compliant mechanisms in suspensions has been explored in the past [6]. In this paper we concentrate on implementing this concept into an existing vehicle. Many different compliant link design concepts were generated. The final concept chosen for development and testing is a variant design which replaces the OEM suspension's upper arm and coil spring with a single, ternary-supported compliant link. A ternary link is defined as a simple link with three pin-joint connections to it. Figure 1 shows a simple configuration of the ternary arrangement used as the upper arm of the suspension. The link is pin-jointed to the wheel carrier at the right end, and pin-jointed to the chassis at the fulcrum. The left end of the link is pin-jointed to a shackle attached to the chassis. The shackle allows for effective length changes of the link as it bends. In this design, the distance from the fulcrum to the wheel carrier joint primarily affects the kinematic behavior of the wheel during bounce and rebound, while the entire length of the link is available for energy storage in the form of elastic strain energy in bending. This approach tends to decouple the design of the link to provide proper kinematic wheel guidance from the design of the link to provide proper vertical stiffness and range of motion, while still utilizing a single element for both functions.

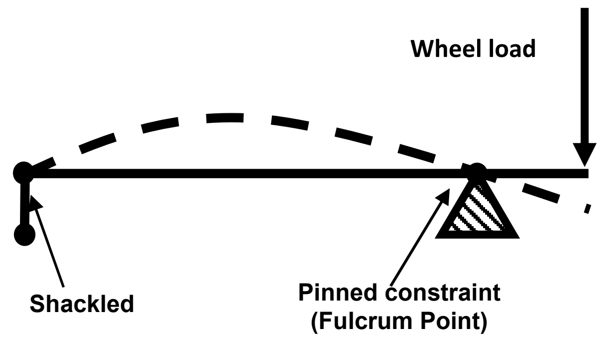

Figure 1: Ternary compliant link

Modifications to the existing rear sub-frame would be necessary to incorporate the ternary compliant link. The most significant of these modifications include the addition of the fulcrum point, and a provision of the shackle and its attachment point.

COMPLIANT SUSPENSION SIMULATION AND MOCK-UP

Multi-body dynamics simulation software, ADAMS, was used to simulate the performance of the compliant suspension. The existing suspension model was built in ADAMS and simulated for its performance characteristics. Once the model of the stock suspension was refined to successfully reproduce the kinematics and compliance test data conducted on the stock suspension, the upper arm of the suspension model was replaced with a ternary supported compliant link. To achieve this, the compliant link was modeled and analyzed using FEA software, ANSYS and a reduced modal description of its dynamic deformation behavior was exported to ADAMS. The resulting model was subjected to quasi-static wheel loads that caused 80mm of bounce and rebound motions to the wheel carrier to predict the elasto-kinematic toe and camber performance of the compliant link suspension. Several parameters on the compliant link including the location of the fulcrum point, length of the compliant link and shackle attachment point were iteratively optimized in an attempt to achieve similar or better results compared to K&C test results obtained on the reference suspension. Once the compliant suspension model was refined to replicate the K&C data of the reference suspension, a test fixture was developed to further validate the compliant suspension concept (Figure 2).

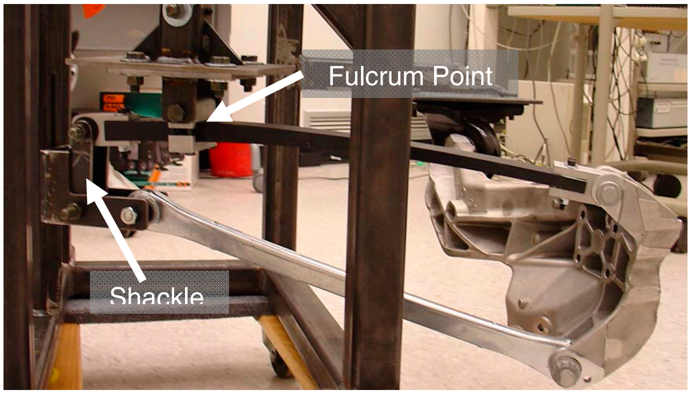

Figure 2 Test fixture containing compliant link as upper link

The adjustable test fixture was built to replicate the suspension hard points found on the rear sub-frame on the OEM vehicle. This test fixture has the ability to accommodate the standard suspension components of the OEM suspension and also the modified compliant link. The upper control arm was substituted with a curved compliant member fabricated by modifying an off the shelf composite leaf spring. Mounting brackets for the shackle and intermediate fulcrum point were added to the test fixture. Measurements of toe and camber changes (toe and camber gradients) versus vertical height change were performed on a Zeiss Pro-T horizontal arm CMM. Similar to the simulations carried out in ADAMS, the test fixture was first tested for kinematics with the standard suspension parts mounted onto the frame. The results obtained from the CMM for the standard suspension part of the OEM was compared with K&C data obtained from tests on the full vehicle to verify the standard suspension parts were functioning correctly in the test fixture. Following that, the upper control arm was replaced with the compliant link, shackles and additional brackets required for the new design and similar measurements were performed. A virtual wheel centerline was derived to measure the vertical compliance of the suspension. The vertical force versus vertical deflection of the suspension was measured using a load cell mounted on a bracket attached to the trailing arm with the loading point at the wheel centerline. The entire test results conducted on the mock-up was further compared with the ADAMS simulation and also the K&C test data of the original vehicle.

TEST RESULTS

This section summarizes the results obtained for the standard as well as the compliant suspension in ADAMS simulation and mock-up of the suspension, compared with K&C test data.

During the refinement phase of the compliant suspension, the mock-up was built with standard suspension parts to verify its kinematic behavior with that of the K&C test data. Figure 3 shows a comparison of the mockup, ADAMS simulation and K&C test data for the suspension with the standard components. The camber gradient for the vertical travel of the wheel carrier showed the expected negative camber in bounce and positive camber in rebound motions and is approximately the same as K&C data, but with a deficit of 0.5 degrees at the extremes of travel.

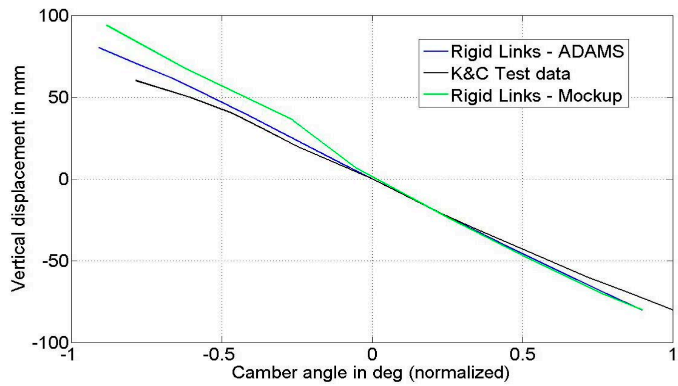

Figure 3 Camber angle v/s Vertical displacement

Once the conformity between test results from K&C, ADAMS simulation, and physical experimentation was achieved for standard suspension components, the upper link on the suspension was replaced with the compliant member. With the compliant member in place the same virtual and physical experiments were repeated. Figure 4 shows the camber angle with change in vertical displacement of mockup of the compliant link suspension,ADAMS simulation of the same and K&C test data for the original suspension.

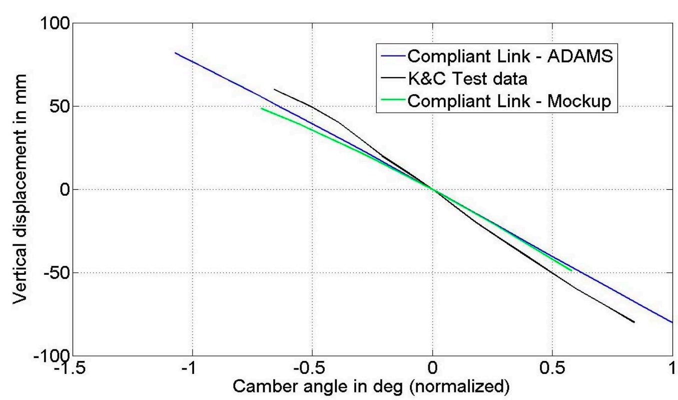

Figure 4: Camber versus displacement (Normalized)

The results show that the compliant suspension produces a slightly more aggressive camber gain compared to the OEM suspension. In simulation and testing we found that changing the static (unloaded) curvature of the compliant link can change the camber gradient of the suspension.

The kinematic analysis of the suspension was also extended to the measurement of toe angle change in ADAMS, which was compared with the mock-up results and the K&C test data. The toe gradient for simulation versus physical experimental data is displayed in Figure 5. The compliant link suspension tended to show higher toe changes than the rigid link suspension. It was observed in simulation that the higher deviations in toe angle can be minimized with the use of a straight compliant link instead of the current compliant link with an initial curvature. However, constraints on available compliant link components did not allow this option to be tested physically.

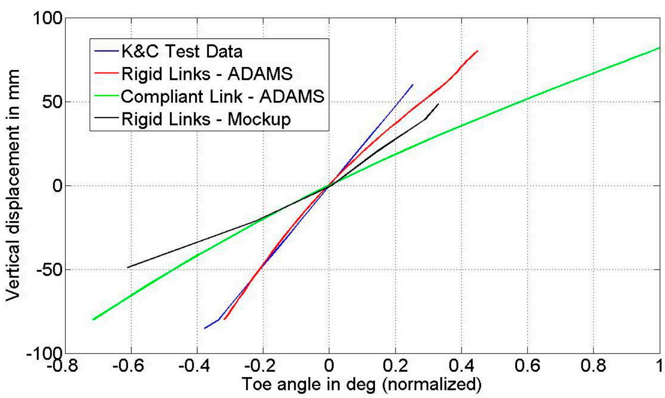

Figure 5: Toe angle versus displacement

The suspension was further analyzed for its response to control forces acting on the suspension and was compared with the OEM suspension results. Figures 6-8 show the response of the suspension to vertical, longitudinal and lateral forces. Since our compliant link was fabricated from an aftermarket composite leaf spring, designed for another application, the vertical and lateral force vs. deflection characteristics matches somewhat with what was provided from K&C data and/or ADAMS simulation of the original suspension. However, we believe that a compliant link suitable for this application can be designed to obtain an improved match in the vertical and lateral stiffness characterstics of the original suspension.

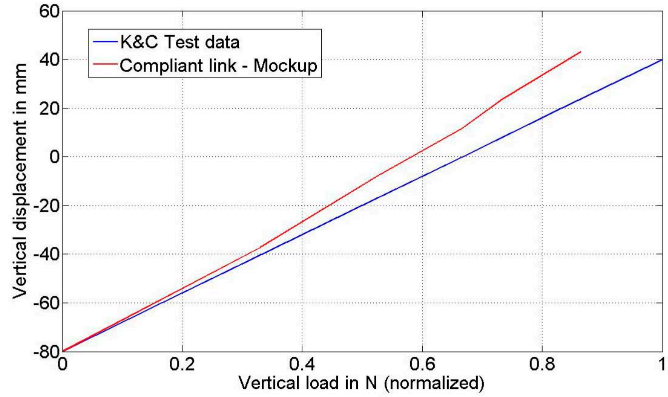

Figure 6: Vertical force versus deflection

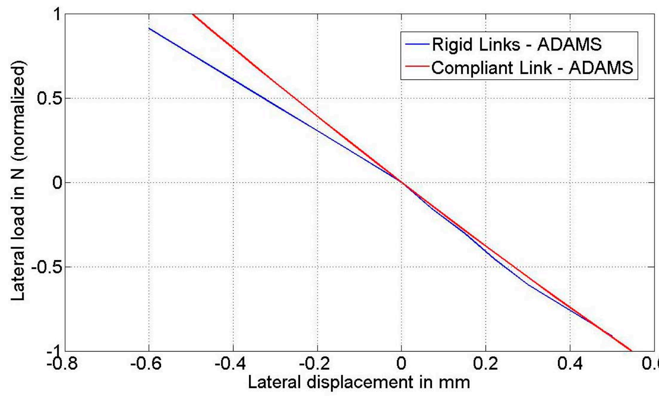

Figure 7: ADAMS simulation of lateral loading.

As can be seen in Figure 8, from ADAMS simulation of the present compliant link suspension, it is noted that the longitudinal force vs. displacement characteristics does not match particularly well with the orginal rigid link suspension. Further work is needed to consider other options such as adjusting hard point dispositions of all links and altering the compliant link geometry to improve the match in this particular response.

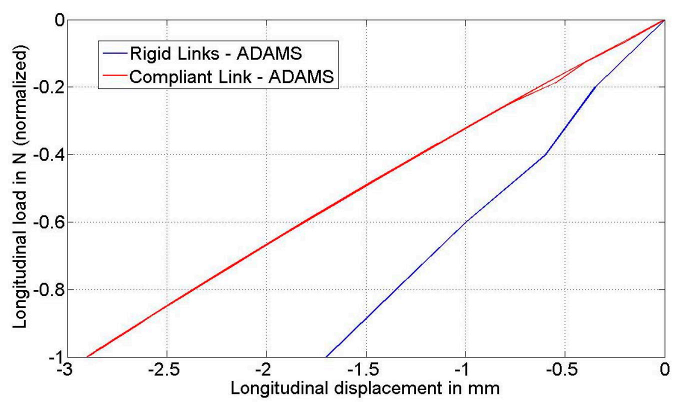

Figure 8: ADAMS simulation of longitudinal loading

CONCLUSION

Based on simulations and experiments, it appears that the ternary supported compliant link can be a viable alternative to a standard coil spring and rigid link in the OEM suspension. Optimization of the link geometry and attachment points is required to duplicate elasto-kinematic performance characteristics of the standard suspension. The ternary supported link allows variations in the length of the link from the fulcrum point to the wheel carrier, thereby enabling wheel kinematics to be somewhat decoupled from vertical compliance. Using an off-the shelf fiberglass leaf spring cut to the design length to replace the upper link of the OEM suspension, we obtained elasto-kinematic behavior similar to the OEM suspension. Additional refinement may be necessary to duplicate the toe angle and longitudinal force response. We believe that with further optimization and detailed control over other design variables on the compliant suspension or even by replacing the lower control arm with an additional compliant link, it may be possible to exactly duplicate the elasto-kinematic performance of the OEM suspension.

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