Investigation of Heavy Vehicle Air Spring Suspension and Load Sharing Characteristics

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1 Introduction

This paper outlines an undergraduate thesis project investigation initiated to elucidate multiple reports of particular air suspended prime movers exhibiting rough ride and excessive air suspended cab vibrations. Subsequently the investigation first quantified the drive and cab suspension parameters.

The drive suspension parameters were identified by passing, at low speed, a near new loaded prime mover over a significant local convex surface protrusion. Here the drive suspension air spring pressure variations were analysed to quantify the suspension parameters in addition to identifying the extent of low speed load sharing characteristics. This 'in motion' testing disappointingly exhibited low signal to noise ratio. In the case of the cab air suspension parameters the signal to noise ratio was improved by conducting additional simplified stationary testing. Again the actual suspension parameters were assessed from analysis of the cab air spring pressure fluctuations analysed.

Causes for the reported vibrations are then discussed as are other implications identified in this test work.

The various phases of this experimental based investigation now follows.

2 Experimental Analysis of the Drive and Cab Suspensions

2.1 Drive Suspension

2.1.1 Experimental Strategy

Testing was conducted by driving the vehicle at approximately 4-6km/h over a steel pipe to provide an impulse to the suspension displacement. The induced suspension displacement versus time variation were recorded and subsequently analysed.

2.1.2 Equipment

Heavy Vehicle (HV): The HV used for the experiment was a loaded 6 x 4 Freightliner Argosy with a single tri axle trailer attached. The vehicle had been in service since 9th May 2006 and had travelled 57297km up to testing. The prime mover steer axle was fitted with parabolic springs whereas the bogie drive suspension was a 4 bag Airliner suspension.

The vehicle axle dimensions are as follows:
Steer to front drive: 3.425m Front drive to rear drive: 1.295m Wheelbase 4.073m

Recorded axle loads:

Steer axle: 5730kg Drive axles: 16500kg Trailer tri axle: 20290kg Total: 42520kg

Surface Protrusion: A 6m length of 48.2 mm outside diameter pipe was positioned on a workshop floor. T-pieces were welded to each end to stabilize the pipe (refer Figure 1) when the vehicle's tyres rolled over it. One end of the pipe was also additionally secured by parking a forklift atop the pipe. The pipe's other end was constrained by steel weights.

Figure 1 Pipe used for suspension vertical disturbance input.

Pressure Transducer: Druck PTX1400 plumbed as close as possible to the front left air spring. The pressure transducer wires were connected to a signal conditioner the output of which was connected to an oscilloscope.

Fittings and Joiners: A 6mm female T-fitting with a 6mm male-male socket was connected along with the pressure transducer and original transmission line connector fitting also attached. Figure 2 depicts the pressure transducer location and plumbing details to the air spring.

Figure 2 Pressure transducer location and plumbing details.

Accelerometer: Endevco model 751-100 attached by super glue to the turntable plate between front and rear drive axles. The accelerometer was electronically connected to a power supply and signal conditioner. The manufacturer's stated sensitivity was 101.8mV/g at 4mA supply current and 1.2% maximum transverse sensitivity. Figure 3 shows the accelerometer location and attachment.

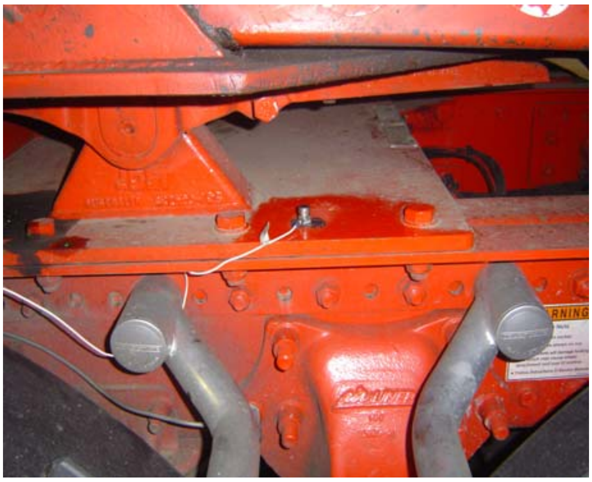

Figure 3 Accelerometer location and attachment.

Signal Conditioner: The signal conditioner was used to transfer output signals from the pressure transducer and accelerometer into voltage signals for display and record on the oscilloscope. There was a separate signal conditioner for both the pressure transducer and accelerometer signals. The pressure transducer response calibration factor was 1.7mV/kPa.

Oscilloscope: Digital two channel Yokogawa DL1520. Throughout the experiment channel 1 (CH1) was used for the accelerometer signal while channel 2 (CH2) was used for the pressure transducer signal. Unfortunately high frequency filtering options were not set for both channels.

Signal Conditioner: The signal conditioner was used to transfer output signals from the pressure transducer and accelerometer into voltage signals for input into the oscilloscope. There was a separate conditioner for both the pressure transducer and accelerometer signals as per the drive suspension test work.

Oscilloscope: Digital two channel Yokogawa DL1520 with soft and hard copy output. Throughout the experiment channel 1 (CH1) was used for the accelerometer signal while channel 2 (CH2) was used for the pressure transducer signal.

Miscellaneous details and equipment: The oscilloscope, PT and accelerometer and power supplies / signals conditioners were mounted onto the vehicle's walk plate as shown in the following figure, Figure 11.

Figure 11 Instrumentation supply and output setup (RHS).

2.1.3 Procedure

All instrumentation equipment previously mentioned in section 2.2.2 was fitted and secured to the vehicle. The cab ride height was checked and found to be 104mm which is the extended length of the air spring. No adjustment was required as the height was within the manufacturer's specifications.

The first test series involved jumping off the cab step and recording the vibration oscillation decay with the oscilloscope. This was effected by standing on the vehicle's step and jumping onto the ground. As the mass was suddenly removed the cab would then undergo damped second order oscillations until it attained its natural equilibrium state.

The second complementary test series involved jumping onto vehicle's cab. This was done by standing on the ground and then jumping onto the cab steps. The purpose of this was to examine the characteristics of the response curve with additional cab mass.

Both of the above tests series were also repeated on the right side of the cab as per the left side. Throughout the tests the equipment was fitted to the corresponding test side. The right side of the cab is essentially a mirror image to that of the left. Figure 12 below depicts the location of the (respective side) step that was mounted and dismounted in this test phase.

Figure 12 Cab step location (LHS).

2.1.4 Results

Similar to the drive suspension experiment, in order to determine the damping ratio and damped natural frequency of the cab suspension, the period of oscillations and the ratio of the decaying oscillations were analysed. Figure 13 and 14 depict response curves corresponding to jumping off and onto the cab left side, respectively. It can be seen that the amplitudes of the oscillations dampen out more quickly when jumping onto the cab relative to that when jumping off the cab.

For each of the four tests, two response curves were obtained (8 curves in total) and the average damped natural frequency and mean damping ratio (DM) calculated.

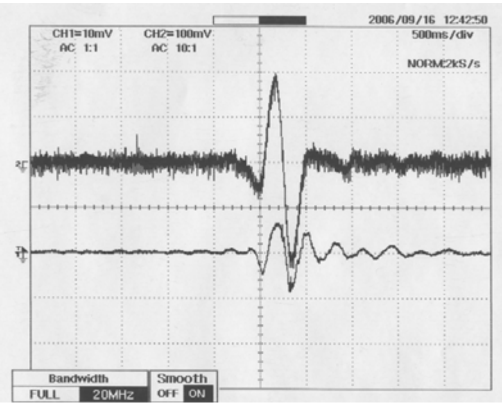

Figure 13 Response curve-jumping off cab.

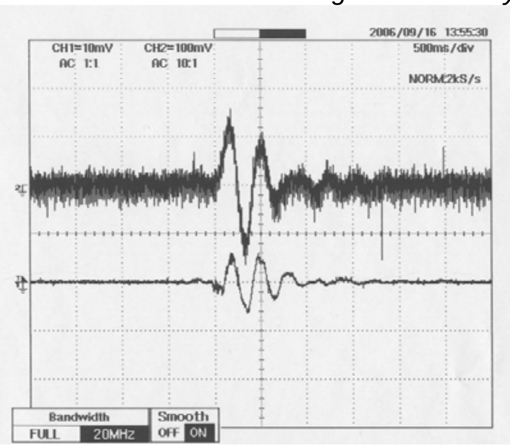

Figure 14 Response curve-jumping onto cab.

The time scale on the ‘x’ axis was set to 0.5 second per division hence to determine the damped natural frequency the number of peaks or bounces in two oscilloscope horizontal screen divisions was assessed to determine the period (T). Subsequently the following damped natural frequencies (f) were observed;

Left side:
Jumping off the cab: f_d= 3.40Hz Jumping onto the cab: f_d = 3.35Hz

Right side;
Jumping off the cab: f_d= 3.22Hz Jumping onto the cab: f_d= 3.16Hz

Averages of left and right sides:
Jumping off the cab: f_d = 3.31Hz Jumping on the cab: f_d = 3.26Hz

The observed mean damping ratio (DM) were as follows;

Left side:
Jumping off the cab: DM = 8.9% Jumping onto the cab: DM = 18.2%

Right side:
Jumping off the cab: DM = 12.2% Jumping onto the cab: DM = 17.2%

Averages of left and right sides:
Jumping off the cab: DM = 10.6% Jumping on the cab: DM = 17.7%

The predicted cab suspension undamped natural frequency is as follows;

Averages of left and right sides:
Jumping off the cab: f_n = 3.33Hz Jumping on the cab: f_n = 3.31Hz

The cab suspension was also tested dynamically (ie ‘in motion’ with the vehicle passing over the surface protrusion) one week prior to the static test. The results however, were influenced by other vehicle excitations which caused excessive noise to signal ratio. Consequently the previous dynamic or ‘in motion’ test data was discarded.

3 Discussion of Results

3.1 Drive Suspension Compliance

Analysis of the response traces indicated the mean damping ratio (DM) was 13%. This indicates the suspension is underdamped relative to the requirements specified in VSB 11 (20%).

The observed damped natural frequency (1.45 Hz) did comply with the certification requirements.

3.2 Pressure Variation Implications

Significant pressure variations were observed in the lead LH drive axle air spring in response to the loaded vehicle orthogonally passing over, at low speed (4-6 km/h), the pipe. The same pressure variations implied significant prime mover axle load variations simultaneously occurred. Notably the lead LH air spring pressure variation displayed several oscillatory responses, depending on which prime mover axle was in contact the pipe. Over the experiment duration of interest the maximum observed increase in the lead LH drive axle air spring pressure was 30% whereas the maximum decrease was some 80%. For the lead drive axle the increase occurred at the instant the lead drive axle contacted the disturbance whereas the maximum decrease occurred immediately after the same axle passed over the abrupt convex disturbance. These pressure variations suggests the instantaneous load on the lead axle first increased by 30% followed, a short time interval after, by a rapid 80% instantaneous decrease. Consequently, due to the rear drive axle's relative proximity, it is estimated the rear drive axle incurs an instantaneous 30% decrease and an instantaneous 80% load increase during the corresponding events experienced by the lead drive axle. It is expected the opposite applies when the rear drive axle passes over the surface protrusion.

Most noteworthy is that, at low speed, individual axles in bogie axle groups incur greatest instantaneous increases in axle load immediately post the adjacent axle symmetrically passing over an abrupt surface concavity.

3.3 Infrastructure Damage

The observed drive axle transient responses post each surface discontinuity, extrapolated to highway speed, has significant implications with regard imposed dynamic air suspended heavy vehicle wheel loads on pavement infrastructure. Implied is that when an air suspended bogie drive vehicle passes over a surface discontinuity at highway speed each axle incurs significant variation in axle loads due to the non optimal dynamic load sharing. The variation in the individual drive axle loads generates, in addition, pitching oscillations of semi trailer prime movers. This pitching associates with extensive steer axle periodic loads. In addition in the drive air suspension 'settling phase', further extensive periodic axle loads occur. Minimisation of these periodic load variations, which, in turn, cause infrastructure damage demands air suspended vehicles operate on pavement surfaces possessing minimal discontinuities (both in number and extent). Infrastructure damage minimisation therefore demands air suspended vehicles operate on highest quality pavement surfaces. That is the latter should exhibit minimal number of acute surface disturbances, especially concavities. Noting the significant periodic load occurrences, especially at highway speed, post concavities or depressions it is not unusual to observe significant infrastructure damage post bridge exit edge plates. Since bridge exit edge plates are ubiquitous unavoidable pavement details considerable infrastructure damage is implied on a national basis.

3.4 Cab Suspension

The observed cab suspension average natural frequency was 3.31Hz when jumping off the cab. A

3.3% discrepancy in the 'jumping off the cab' DM was observed between the left and right sides. This could be due to a number of factors including; a variance in cab weight distribution symmetry, instrumentation and control conduit location bias, steering column shaft influence and differences in the shock absorber efficiency.

As expected, the observed DM is greater when jumping onto the cab relative to that when jumping off the cab. This is because jumping and staying on the cab incremented the cab suspension's suspended mass. This, in turn, moves the cab suspension damping ratio closer to a critically damped system in accord with the theoretical predictions for damped second order systems.

The former indeed confirms the cab suspension parameters are dependent on the suspended mass. The cab suspension exhibited an average undamped natural frequency of approximately 3.3 Hz and an average mean damping ratio not exceeding 18%.

The undamped natural frequency of the cab right side was less than that of the left side. However, the RHS exhibited greater sensitivity of same with changing mass relative to that exhibited by the LHS. In regard the damping ratio the opposite sensitivity, with the suspended mass component, was observed between the left and right sides. It is expected the bias of the steering column, gear selector, cab internals and cabling partially account for the observed differences.

3.5 Integrated Effects

Luckily the observed drive and cab suspensions undamped natural frequencies differed and were not exact integral multiples of each other. Notably if the drive suspension frequency matched the cab suspension undamped natural frequency, significant resonance would be exhibited by the cab suspension. If subjected to such resonance conditions, the cab suspension would oscillate at amplitudes the cab shock absorbers would find difficult to dampen effectively.

In regard possible harmonic effects the cab suspension's undamped natural frequency was within 11% of the second harmonic of the drive suspension's undamped natural frequency. It is expected this difference would adversely diminish at those times the cab suspended mass is at the more typical in service value. Particularly with the driver and /or passenger present and cab luggage and sustenance stowed within the cab.

3.6 Experimental Influences

The overall dynamics of the drive and cab suspensions are complex systems that have a significant number of variables that could all contribute and have influences on the actual operational behaviour. Following are some items that may have influenced the experimental results:

Shock absorber condition. Although the vehicle was relatively new and only had travelled 57297 km , there is a possibility that the shock absorbers are not functioning as designed.

System Noise The in motion response plots, particularly the accelerometer output, did contain some undesirable noise due to the location of the test equipment. Adverse extraneous noise sources included: engine generated noise, drive line and vehicle motion dynamics. Further exacerbation of the noise may have occurred due to feedback to the power supply box, signal conditioner, instrumentation and oscilloscope as the result of mounting the same on the walk plate. Although undesirable, there was no option other than to mount all the 240 AC voltage equipment on the vehicle's walk deck. The accelerometer displayed lower signal to noise ratio relative to the pressure transducer output. Due to the higher signal to noise ratio, only the pressure response traces were used to obtain the suspension parameters.

Pressure Transducer Location Where possible the pressure transducer (PT) was fitted as close as possible to the corresponding air spring for both experiments. The drive suspension experiment enabled fitment of the PT relatively close to the air spring. In comparison the cab experiment required a 140mm long length of 6mm air line to be fitted between the PT and air spring. It is estimated, for this relatively low speed test work and low frequency pneumatic system, the pressure transducer adequately ‘dynamically’ tracked the actual cab air spring pressures.

Trailer Load Influence Typical bulk trailer loads also have damping properties which indirectly influence the characteristics of the suspension dynamics. At the time of testing the trailer was bulk loaded with scrap steel swarf disks which were significantly densified after inter capital city haulage to the test site. It is postulated the load exhibited minimal damping parameters.

3.7 Investigation Enhancements

Possible investigation enhancements include:

Use a surface discontinuity as per that specified in VSB 11 in lieu of one possessing an extremely bluff lead surface discontinuity such as a pipe as used in this investigation. Disappointingly the surface discontinuity profile recommendations of VSB 11 were closely approximated by heavy vehicle wheel elevation ramps available at the test site. These ramps (based on 75 x 75 mm RHS construction), with favourable lead in slope, would have generated a step drop comparable to that demanded in VSB 11. It is expected, if utilised, improved signal to noise ratio measurements would have resulted.

Simultaneously monitor:

- both the LH and RH cab air spring pressure variations,
- all four drive axle air springs internal air pressures (ie lead and rear drive axles both LHS and RHS),
- both the lead and rear drive axle, and if resources permit, the steer axle vertical displacements (relative to the chassis rails) using suitably fast response string potentiometers or the vertical accelerations of the same axles,
- the relative vertical displacement between the chassis rail and the cab floor,
- near turntable centre line, cab floor, above steer axle chassis rail and driver seat pad vertical accelerations.

Monitor the system response using a mobile stand alone on board 16 channel (say) data logger logging at (say) 10 ms intervals.

Determine the chassis vertical modal frequencies.

In all cases test work should be conducted in at least triplicate test runs with each test run suitably triggered to enhance test data interpretation.

The cab and seat suspension parameters should be ascertained using dynamic testing with the driver situated as per normal driving position with the cab tare appropriate to the in service stowage extent.

3.8 Drive Axle Dynamic Load Sharing Characteristics

The drive suspension air pressure response curves indicate the drive suspension was not effectively dynamically load sharing. Namely had the suspension exhibited optimal dynamic load sharing the pressure variation would be minimal whilst passing over a surface obstruction. Especially in view of the relatively low test speed (4-6km/h). The significant pressure variations is caused by the insufficient air transfer between the drive axle air springs, along each side. This insufficient air flow is controlled, in turn, by the deficient conduit diameter. The required conduit size may be evaluated noting the distance between the front and rear drive axles and noting the reaction time should not exceed 0.78 seconds to be dynamic load sharing (at the test speed). Using similar calculation methods to Davis (2006 c), the optimal inter air spring connection conduit diameter for the suspension to effectively load share at the low speed of 6km/h would be 10.2 mm. This diameter is significantly larger than the standard internal diameter.

From gaining an understanding of the speed of response and the effects this has on the suspension, a recommendation for improving the load sharing capabilities would be to use larger diameter transmission lines. This would not only influence the dynamic load sharing characteristics of the suspension but also reduce shock loads and other dynamic effects.

3.9 Experimental Improvements

To assist analyse the road friendliness of air suspensions it would be beneficial to device a common test equipment that could be used across all vehicle makes.

One alternate static test system would be to pull down the chassis compressing the air springs. The system should then be suddenly released so generating relatively noise free, clean oscillations of the system. To eliminate the action of the height control valve the same should be conveniently disconnected. Subsequent recording of the chassis oscillations should be ascertained using pressure transducers closely connected to the air springs and/or by an accelerometer mounted to the frame. This test would be more convenient and safe relative to the nominated displacement transducers specified in VSB 11.

A single test standard would allow a more accurate way of comparing the characteristics of one suspension relative to another. This devise could be used to access compliance for road friendly certification and diagnostics of suspensions including their performance and the component state of repair (ie shock absorber status).

3.10 Static Load Sharing Compliance

Despite the obvious dynamic load sharing deficiency the vehicle used in the analysis likely complies with VSB 11 in regards to load sharing performance as the requirements within the Bulletin are for **static** load sharing only. Noting this major deficiency there is strong need for a revision.

3.11 Expected Causes for Adverse Vehicle and Cab Vibrations

The possible causes for the vehicle adverse vibration characteristics include:

Firstly both the drive and cab suspension were identified to exhibit deficient damping (13 & 18%, respectively).

Secondly both the drive and cab suspensions exhibit relatively low undamped natural frequencies (1.46 and 3.3 Hz, respectively). Such low frequencies are adverse in regard to whole body human response (ISO 1997).

Fourthly as observed, the cabin's natural frequency was adversely within 11% of the second harmonic of the vehicle's drive suspension natural frequency.

Noting the presence and significance of low frequency vibrations it only remains to identify possible sources of low frequency excitation, at highway speed, to the connected (via the chassis transmission path) drive and cab suspension systems. This identification differs greatly to the typical high frequency excitations itemised by Sweatman and McFarlane (2000). The predominant low frequency excitation exhibited, particularly, by semi trailer prime movers is that due to prime mover pitching. This pitching is, in turn, generated by the road pavement conditions (eg bump extent and spacing) accentuated by the bogie suspension's adverse dynamic load sharing characteristics. The presence of significant low frequency excitation to typical prime movers is readily apparent from an examination of, in particular, Figures 10, 12, 13 and 14 (Sweatman and McFarlane (2000)). For the particular test vehicle the predicted range of pitching frequency is 2.9 – 4.1 Hz. The possibility of sub harmonic resonance also occurs.

4 Conclusion

Significant information and improved understanding of the air suspended bogie drive and cab suspensions vibration characteristics of a typical near new cab over 6 x 4 prime mover was gleaned using simple, convenient and readily available instrumentation. Notably the observation, recording and subsequent analyse of each suspension's response, to a sudden disturbance facilitated quantification of the paramount suspensions vibration parameters. Here the suspension parameters were readily identified using standard damped second order system analysis of the system's free response post a suitable sudden disturbance. The unitary unforced pressure response generated by the rear axle passing over the disturbance exhibited the highest signal to noise ratio. Hence this final year engineering thesis project identified and conveniently quantified the drive suspension's vibration parameters including the state of repair of the vehicle's drive suspension shock absorbers. The drive suspension was noted to exhibit non optimal low speed dynamic load sharing characteristics.

Significant drive axle load time variations are implied by the observed lead LH air spring pressure variations generated when the test prime mover passed over the abrupt convex surface continuity. These variations included a instantaneous disturbance followed by a subsequent transient free response phase. The observed inadequately underdamped periodic load variation has significant implication in regard infrastructure damage post road surface discontinuities. This test work suggests greater load variations occur when one of the drive axles experiences a sudden surface depression relative to that when the same contacts a sudden surface protrusion. This observation suggests determination of the drive suspension parameters using displacement transducers alone, as recommended in VSB 11, is inferior to the use of pressure transducers to identify the paramount suspension parameters. Notably use of the former eliminates opportunity to identify the extent or otherwise of dynamic load sharing between axles in OEM heavy vehicle axle groups (via identification of pressure overshoots and/or extensive pressure undershoots).

5 References

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