Available online at www.sciencedirect.com

ScienceDirect

Journal of Terramechanics 57 (2015) 41–59

Journal of Terramechanics

www.elsevier.com/locate/jterra

Research Paper

Comparison of different gas models to calculate the spring force of a hydropneumatic suspension

S. Francois van der Westhuizen, P. Schalk Els *

University of Pretoria, Corner of Lynnwood Road and Roper Street, Pretoria 0002, South Africa
Department of Mechanical and Aeronautical Engineering, University of Pretoria, Private Bag X20, Hatfield 0028, South Africa

Received 27 January 2014; received in revised form 13 October 2014; accepted 29 November 2014
Available online 20 December 2014

Abstract

When developing any simulation model some compromise must be made between computational efficiency and the accuracy of the model. This study compares the performance of three ideal gas (IG) law variations (IG with the energy equation (EE), isothermal and adiabatic), and two real gas approaches (Benedict Webb Rubin (BWR) equation with and without the EE) to model the spring force of a hydropneumatic suspension. These models are compared with experimental data obtained from laboratory tests on a single hydropneumatic suspension unit. Both the BWR and IG models with the EE offer a significant improvement in correlation compared to the models without the EE. The real gas BWR approach offers a small improvement over the IG approach under the test conditions. The best (BWR with EE) and worst (IG isothermal) models are then used to model the spring forces in a full vehicle model of a 4×4 Sports Utility vehicle (SUV). The data is again compared with experimental results and the BWR model with the EE correlates significantly better than the IG isothermal model. It is thus concluded that the inclusion of the EE will yield significantly better results and it should only be omitted if the parameters investigated are not sensitive to errors in the spring model.

Keywords: Vehicle simulation; Hydropneumatic suspension; Suspension modelling; Spring modelling; Gas modelling; Model verification; Energy equation; Benedict Webb Rubin; Real gas

1. Introduction

Using modern day technology a design can be verified and adjusted before production, by using simulation models. Due to the complexity of highly detailed models a compromise is often made between ease of use, computational efficiency and model accuracy. Full vehicle models often contain a large number of sub-models. This means that a small error in the results of a sub-model can have a significant effect on the overall result. This also allows for the possibility of a model working well for a certain case due to the effect of the errors being small or due to the errors cancelling out and thus having a small net effect. The result is that the model will not give good results when modelling other cases. This is emphasised by Kat and Els (2012) who states that simulations offer great advantages over physical prototypes, but in order to obtain meaningful results the model should be validated using the correct parameters. Bernard and Clover (1994) define validation within the

Abbreviations: BWR, Benedict Webb Rubin; DLC, double lane change; EE, energy equation; IG, ideal gas; RE, relative error; SUV, Sports Utility Vehicle

* Corresponding author. Tel.: +27 12 420 2045; fax: +27 12 362 5087.
E-mail addresses: FrancoisVd@bell.co.za (S.F. van der Westhuizen), schalk.els@up.ac.za (P. Schalk Els).

http://dx.doi.org/10.1016/j.jterra.2014.11.002
0022-4898/

Nomenclature

a	BWR constant
A_0	BWR constant
b	BWR constant
B_0	BWR constant
c	BWR constant
c_v^0	ideal gas specific heat constant
c_v	specific heat constant
C_0	BWR constant
h	time step
m	mass
n	polytropic constant
N_1 to N_9	specific heat constants
P	pressure (subscripts: 1 – initial state, 2 – current state)
$\dot{Q}$	heat transfer rate between the system and the environment
R	universal gas constant
t	time
T	temperature (subscripts: 1 – initial state, 2 – current state)
T_s	atmospheric temperature
T_g	gas temperature
$\dot{T}_g$	change in gas temperature
$\dot{u}$	change in specific internal energy of the gas
$\dot{U}$	change in internal energy of the gas
$\dot{v}$	change in specific volume
v	specific volume
$\dot{V}$	change of volume
V	volume (subscripts: 1 – initial state, 2 – current state)
V_0	initial volume
$\dot{W}$	work done by the piston on the gas
y	specific heat constant
m%RE^m	modified mean percentage relative error
P (%)	probability
Greek symbols	
α	BWR constant
β	bulk modulus
γ	BWR constant or adiabatic index (context dependant)
τ	thermal time constant
ΔP	change in pressure
ΔV	change in volume

context of vehicle simulation as: "the process of gaining confidence that the calculations yield useful insight into the behaviour of the simulated vehicle."

Hydropneumatic suspensions are widely used in off road applications due to the ease with which the characteristics can be changed. According to Bauer (2011) almost every suspended tractor front axle uses hydropneumatics. The Dynamic Truck Suspension by Vehicle Systems Engineering (VSE) VSE, 2013 is another example of a hydropneumatic suspension used for military and off road rally applications. Large construction vehicles, e.g. dump trucks, often use hydropneumatic suspension systems due to the high energy density, and thus small space requirements compared to steel springs and dampers. Thus to build an accurate vehicle dynamics model of these vehicles, a good hydropneumatic suspension model is necessary. During a study on slow active suspension control of a hydropneumatic suspension by Van der Westhuizen and Els (2013) some concerns were expressed regarding the accuracy of the Ideal Gas (IG) law to model the spring. In this study it was decided to rather use a real gas approach which should be more accurate than the IG approach, but the validity of this assumption has not been verified. This study will therefore quantify the accuracy gained by using a real gas approach with and without heat transfer compared to an IG approach with and without heat transfer. The best and worst models are then used to model the spring in a full vehicle model and the results are compared with experimental data.

The suspension used in this study is the $4S_4$ (4 State Semi-active Suspension System) developed by Els (2006). A schematic diagram of a $4S_4$ unit can be seen in Fig. 1. It consists of two hydropneumatic springs combined with two hydraulic dampers. If valve 3 is closed only the small gas volume in accumulator 1 is compressed resulting in a stiff spring characteristic. If valve 3 is open the larger gas volume in both accumulators are compressed resulting in a soft spring characteristic. If valves 1 and 2 are closed the system delivers high damping and low damping if they are open. The volume of accumulator 1 and the damping characteristics of damper 1 have been optimised for handling by minimising the body roll angle when performing a severe double lane change (DLC) manoeuvre. This represents the "handling" setting. The combined gas volumes of accumulators 1 and 2, as well as the combined characteristics of dampers 1 and 2, with valve 1 and 2 open, have been optimised to minimise the vertical acceleration on the vehicle whilst driving over rough Belgian paving terrain. This represents the "ride comfort" setting. The $4S_4$ can switch between "handling" and "ride comfort" settings in less than 100 ms. Switching between the different settings occur automatically based on acceleration measured on the vehicle body. The switching is performed by opening or closing solenoid valves. This suspension has been implemented successfully on a Land Rover Defender 110 at the University of Pretoria. Take note that the dampers shown in Fig. 1 were removed for the gas model validations described in Section 3.2.