AIR SUSPENSION DESIGN AND PERFORMANCE

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SYNOPSIS

This paper gives information on air suspension design considerations and performance characteristics under the following section headings :

(1) Introduction
(2) Theory
(3) Air Suspension Components
(4) Levelling Valves
(5) Application

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SECTION 1 INTRODUCTION

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SECTION 3 AIR SUSPENSION COMPONENTS

SECTION 4 LEVELLING VALVES

SECTION 5 APPLICATION

1. INTRODUCTION

The development of air suspension goes back nearly a century when early airsprings were manufactured using leather.

It was not, however, until the mid 1930's that airsprings were seen on a production vehicle, when they were fitted to an American car. This was soon abandoned due to rubber prices fluctuation and on-going development of steel as a suspension media.

Consequently, it was not until the 1950's that air suspension as we know it today evolved.

With the rapidly changing demands of the transport industry, the suspension engineer is faced with the need for a multi-function system that does more than simply suspend a body above an axle.

It is with this thought in mind that air suspension offers considerable scope.

2. THEORY

The static load capacity of an airspring is expressed, generally, by:

$$F = pA \tag{2.1}$$

Since both the pressure and area can change during the relative movement of one mounting surface to the other, the stiffness of the airspring can be written:

$$\frac{df}{dh} = p\frac{dA}{dh} + A\frac{dp}{dh} \tag{2.2}$$

However, since the motion of the airspring is rapid, the gas temperature changes and is subject to the gas laws.

Consequently, for dynamic conditions, and it is these that apply to a vehicle in motion, we have:

$$\frac{df}{dh_a} = p\frac{da}{dh} + An\frac{dp}{dh} \tag{2.3}$$

It is generally accepted that the polytropic constant $n = 1.38$

Further expansion of equation 2.3 yields:

$$\frac{df}{dh_a} = p\frac{dA}{dh} + An\left(-\frac{1}{V}\frac{dV}{dh}\right)(p + pa) \tag{2.4}$$

Thus, the stiffness of an airspring comprises of two distinct terms - an area function and a pressure/volume function.

In addition, for a given airspring installation condition, both $\frac{dA}{dh}$ and $\left(-\frac{1}{V} \cdot \frac{dV}{dh}\right)$ An are, generally, constants.

Subsequently, it can be readily seen that the stiffness of an airspring is substantially proportional to the load pressure. This is particularly true at higher pressures where the atmospheric pressure term, pa, has least influence.

Hence, the airspring is a device whose stiffness is proportional to the load that it carries and, thus, has a variable rate characteristic.

It is this characteristic which is so important to the suspension engineer in his requirement for constant ride quality for a varying payload.

Figures 1 and 2 illustrate the dynamic spring rate and natural frequency, V, static load characteristics for an airspring.

How can we further modify the performance of an airspring for a particular installation?

We have seen from equation 2.4 that the stiffness comprises, in principle, of two terms. Let us now consider a particular airspring and its supported load, hence, pressure and area are defined since $F = pA$; equation 1.

Firstly, we will consider the $p \frac{dA}{dh}$ term.

This can be modified for the rolling diaphragm airspring by changes in piston profile. Naturally, this does not apply to the bellow type airspring.

Secondly, we will consider the an $(p + pa) \left(- \frac{1}{V} \cdot \frac{dv}{dh}\right)$ term. Here we can alter the value of the term for both bellow and rolling diaphragm airsprings by increasing or decreasing the volume.

Thus,

$$\frac{df}{dh} = p . \frac{dA}{dh} + An, \frac{dp}{dh} . \frac{V}{V + v} \qquad (2.5)$$

or $$= p \frac{dA}{dh} + An\ (p + pa) \left(- \frac{1}{V} \cdot \frac{dV}{dh}\right) \frac{V}{V + v} \qquad (2.6)$$

Thus, we have a unique product which has:

(a) Near constant frequency for a large variation in supported load.

(b) A means of varying its dynamic properties to enable the suspension engineer to fine tune.

3. AIR SUSPENSION COMPONENTS

3.1 Airsprings

There are three basic types:

(a) The convoluted bellow airspring which can compromise one, two or three convolutions of the rubber/fabric element. Fig. 3

(b) The rolling diaphragm airspring which comprises a cylindrical rubber/fabric element, which can have a self sealing bead at both ends, a top mounting plate and a lower piston.

The cylindrical element when assembled and inflated forms a lobe which can roll up and down the piston to accommodate suspension motion. Fig. 4

(c) The rolling diaphragm airspring which can be adapted to work as a heavy duty unit by the addition of a metal sleeve to the exterior. Fig. 5

As previously stated, a characteristic of the airspring is that its dynamic rate varies substantially in proportion to the instantaneous value of the static load pressure.

This statement applies particularly well for load conditions where the load pressure is very high and the constant term for atmospheric pressure has less effect.

The effects of application of this characteristic to the vehicle are illustrated by the curve of bounce frequency (hz) v. sprung mass (kg) for an air spring supporting a simply supported mass. Fig. 6

Since the airspring stiffness is of finite value at zero static loading (due to the presence of the P.atm term in the equation for spring stiffness), the theoretical value for bounce frequency at zero load pressure is infinity.

However, as sprung mass is increased bounce frequency quickly stabilises at a near constant value, until a load pressure value is reached wherein little or no further change in bounce frequency occurs at all for further increase in load pressure.

This characteristic thus describes an apparent ideal situation which has the following advantages:

- high static load pressure allows construction of small airsprings providing easier installation.

- low vertical stiffness, low bounce frequency.

- allowing say 50% change in sprung mass, near constant bounce frequency, laden to unladen.

- thus optimum damper tuning, laden to unladen, hence absolute anti-vibration control.

- since application of the high pressure airspring requires the provision of a HP circuit, possible realisation of full closed-loop body to earth positional control is established through the levelling system.

It is considered that the convoluted bellow, rolling diaphragm and heavy duty rolling diaphragm airsprings will satisfy the commercial vehicle industry's suspension needs for some time to come.

The needs of the commercial vehicle industry for the 21st Century are less easily defined, but with the advent of the "micro-chip" and the move towards "system management" it is considered that an active suspension system offering improved ride/handling and packaging may be required.

With this in mind, Dunlop have examined what type of spring element would be required. A Hydro-pneumatic system has been considered and is now described.

THE HYDRO-PNEUMATIC SYSTEM

The Basic System

The principal features of a hydro-pneumatic suspension for a bus are shown in - Fig.7

The road wheel input operates on a rolling lobe liquid displacer which causes the volume of a liquid/gas sphere to vary with the input.

The liquid/gas sphere comprises, two compartments which are separated by a flexible membrane..

The volume of liquid displaced by the rolling lobe displacer is transferred to, or from, the sphere thus causing an equal change in the gas volume via expansion or compression.

Suspension stiffness at the road wheel, is governed by fluid displacement as defined by the application of Gas Law and airspring theory.

Design Features

Dunlop's considerable experience with the design and manufacture of the Hydrolastic and Hydragas systems has enabled specific design parameters to be laid down which are compatible with current technology.

The preliminary specification is shown in the following table:

Spring element capacity: design	6000 lb
Spring element overload	15%
Maximum static load pressure	400 psig
Maximum system pressure	approx 1000 psig
System burst pressure	approx 3000 psig
Wheel travel	Rebound 4" Bump 3"
Operating temperature range	-50°C to +50°C

System to be self levelling for changes in payload.

In order to compensate for changes in payload and temperature a levelling system is considered to be of paramount importance. Thus, in addition to the fluid displacer and gas spring, a levelling sphere is incorporated in the system.

The levelling sphere is identical to the gas spring sphere. The gas compartment of the gas spring and levelling sphere are interconnected whilst the liquid side of the levelling sphere is connected to a pressurised supply which is controlled via a levelling (height) valve.

Changes in payload will cause the design height of the displacer to change unless the mass of gas in the gas spring is adjusted.

This adjustment is therefore achieved by transferring gas to, and from, the levelling sphere via displacement of its separator membrane.

Separator membrane movement is controlled by the modulation of pressurised liquid against it.

Since the gas spring and levelling spheres are interconnected the effect of gas volume changes will have a significant effect upon the stiffness of the system.

Consequently, the two spheres are isolated during normal steady state payload conditions in order to provide a constant volume gas spring.

The two spheres are only interconnected when there is a change in payload, and this function is controlled via the levelling system.

The dimensions of the principal components of the system are shown in - Fig. 8

Levelling System

The levelling system consists of:

- an engine-driven high pressure hydraulic pump which supplied liquid (usually oil) to the levelling or height valve.
- a 3-position directional control valve which controls the supply of liquid to, or from, the levelling sphere.
- a 2-position pilot operated valve interposed between the gas spring and levelling spheres, operated via the levelling valve.

According to the nature of the signal high pressure liquid is delivered to or exhausted from the levelling sphere, via the levelling valve, to a reservoir.

4. LEVELLING VALVES

The levelling valve is a 3 positional directional control valve employed for the supply of compressed air to and from the airspring in response to changes in payload, thereby, maintaining a constant ride height.

In general terms, the construction of levelling valves can compromise either of two types:

(a) the delay levelling valve Fig. 9
(b) the no delay levelling valve Fig. 10

The construction of the delay type valve is such that there is time lapse (2-6 seconds) between the input signal and the opening of an air valve stage.

Consequently, the valve does not respond to transient wheel inputs and conserves the store of compressed air.

However, the delay levelling valve is complex, expensive and may not meet the stringent requirement of repeatable levelled position.

Consequently, the no delay levelling valve was developed with the objectives:

(1) Improved levelling accuracy
(2) Minimum air consumption
(3) Reduced cost
(4) Three years minimum service life

Subsequently, vehicle development which included air consumption measurement, suspension charge times combined with ride and handling indicated that a valve with restricted service port flow characteristics fulfilled the basic objectives.

Typical results, appertaining to a coach, are shown in Tables 1 and 2.

With the advent of the micro-chip and systems management, it is possible to devise an elctro-mechanical system which continuously monitors the suspension attitude and makes adjustments according to a pre-arranged programme.

Initial investigations indicate that such a system will provide:

- accurate positional control
- improved system reliability
- the opportunity to "fine tune" a levelling system to suit a particular vehicle requirement.

Dunlop are therefore, examining how this electronic system can be extended to form an integral part of an air suspension system.

In this respect, a single deck air suspension city bus has been fitted with an electronic levelling system. Development evaluation is on-going.

The basic system comprises a photo-electric sensing device which transmits a signal to an electronic control unit. The ECU compares the signal with a reference level, appropriate changes to the airspring height are then actioned, if necessary. Fig. 11

The use of such a system goes beyond that of the basic levelling function, it offers:

(i) Raise and lower of suspension for container handling.

(ii) Ride height datum shift to allow ease of entry to, or exit from, ferry.

(iii) Variable, continuously levelled, vehicle platform height to accommodate different loading bay heights, i.e. re-defined static ride height.

(iv) Individual control of each wheel station, i.e. front kneel rear kneel, offside, nearside etc..

With further development it is envisaged that the ECU memory could hold vital diagnostic information with regard to overall performance of the vehicle suspension behaviour.

5. APPLICATION

The wide range of payloads that a suspension system has to operate over are shown in - Fig. 12

The effect of this change in payload, for three types of suspension media, on the bounce frequency, is illustrated in - Fig. 13

5.1 Semi Trailer

The ride characteristics of a number of semi-trailers fitted with different types of suspension have been analysed.

Trailer 1	Rubber suspension
Trailer 2	Standard multi-leaf suspension
Trailer 3	Air suspension

Acceleration measurements were taken above the trailer axles for the part laden - the most often met condition - and empty conditions.

The vehicles were then driven at 40 miles per hour over a standard test surface.

The recorded data was then analysed to produce both 1/3rd octave acceleration frequency spectra and a measure of the peak acceleration levels recorded over the test surface.

Each acceleration frequency spectrum depicts a plot of the r.m.s. 'g' level (vertical axis) contained in each 1/3rd octave frequency band (the centre frequencies of each band are shown on the horizontal axis) over the frequency range 0 - 100 c/s together with the overall r.m.s. 'g' levels in both the "ride frequency range" of 0 - 40 c/s and the range over which measurements were recorded (0 - 100 c/s). These levels are shown on the spectrum as "linear" levels and are a summation of the 1/3rd octave levels over their respective frequency ranges. These frequency spectra are shown on Figures 14 and 15.

The overall r.m.s. 'g' levels in the 0 - 40 c/s frequency range have been plotted against the various trailer configurations in Figure 16. These provide a means of comparing the riding properties of each trailer under each of the various test conditions in a less detailed form.

Peak acceleration levels are shown in Figure 17 for the two frequency bands 1 - 8 c/s and 8 - 40 c/s.

In conclusion, it will be noted that the air suspension trailers produced acceleration levels much lower than those of the other types and would therefore, provide a significantly better ride resulting in less damage to the vehicle and its cargo.

5.2 Bus

Ride measurements for the upper deck of a city bus are shown in - Fig. 18

5.3 Road Damage

In addition, research conducted by M.I.R.A. and T.R.R.L. has indicated that a correctly damped low rate suspension reduces road damage. An important factor in today's environmental conscious world.

To conclude, an air suspension system offers:

1. Variable rate suspension.
2. Constant ride height.
3. Near constant ride frequency for large changes in payload.
4. Protection to vehicle, cargo and driver.
5. Development of electronic mult-function levelling system.
6. Development of high pressure system to improve packaging.
7. Reduced road damage.
8. Improved braking.

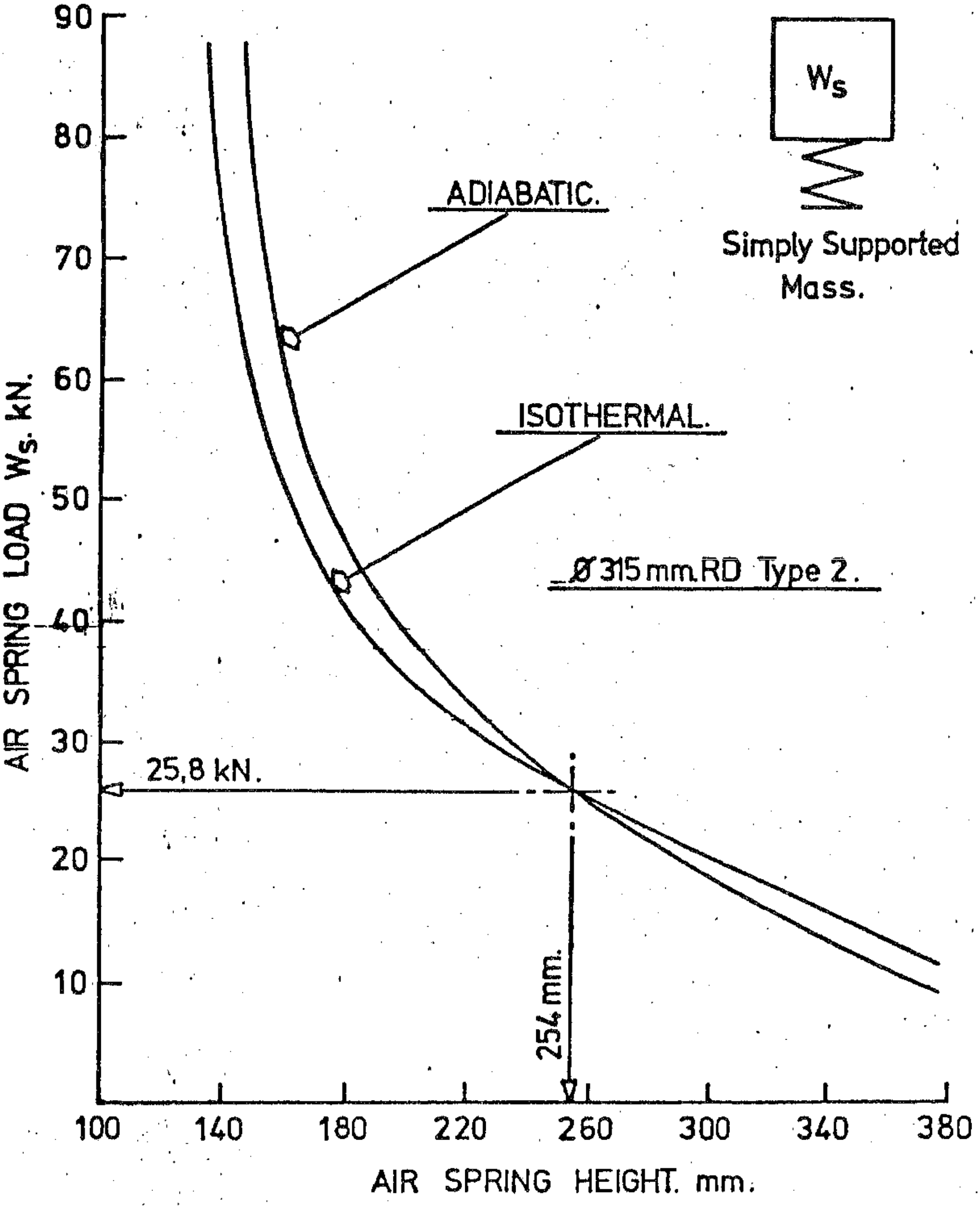


FIG. 1 LOAD/DISPLACEMENT CHARACTERISTIC.

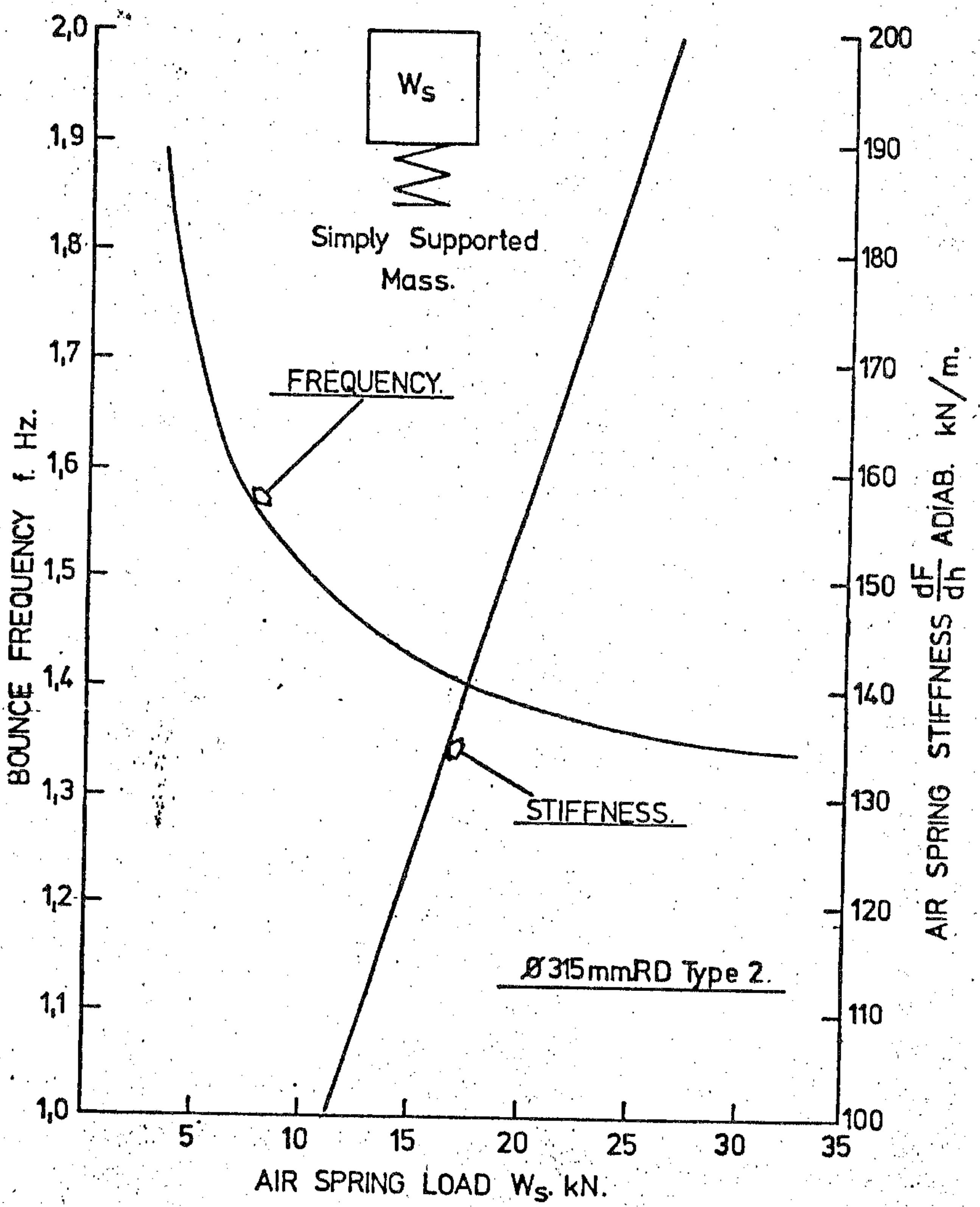
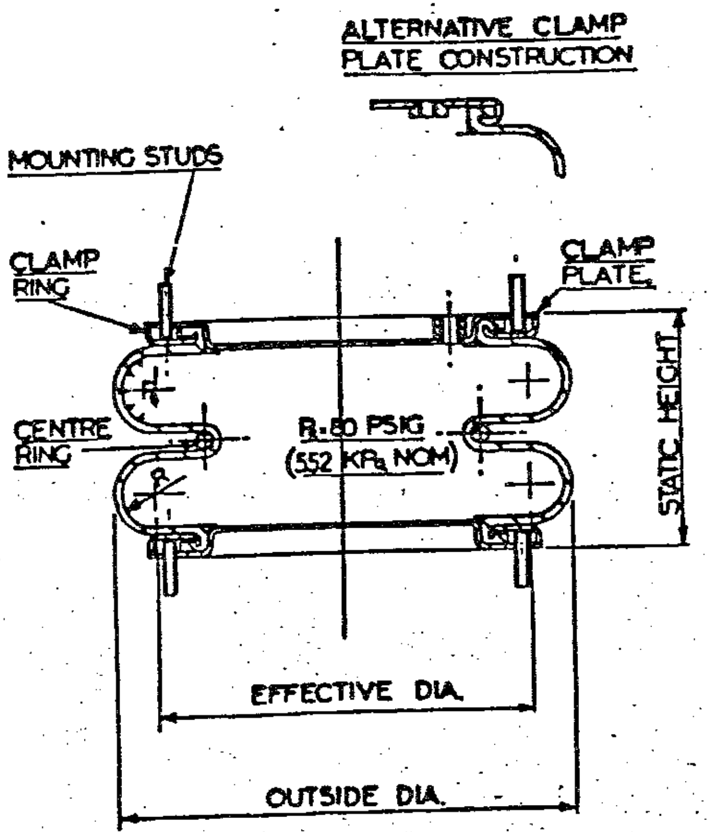
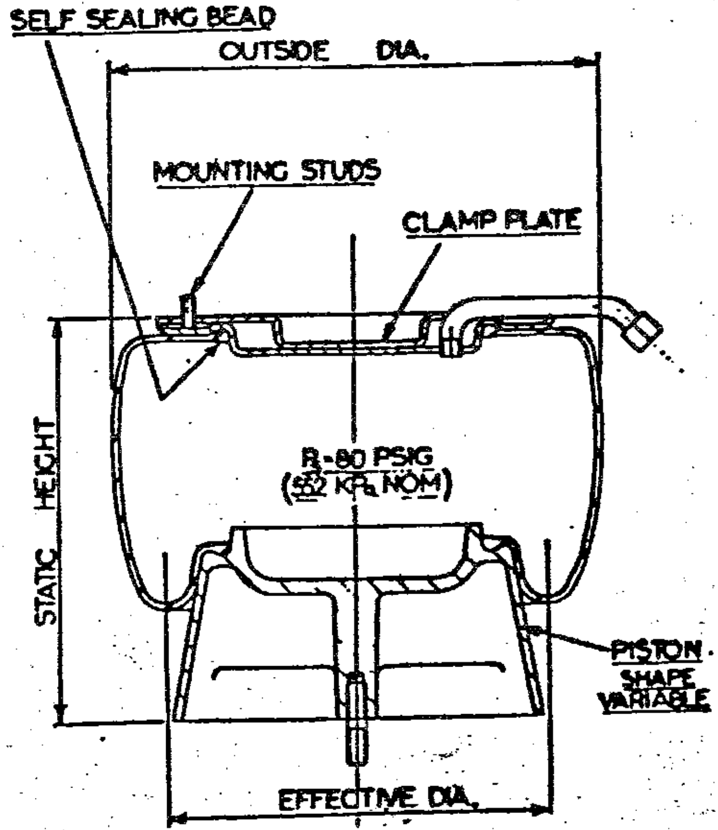


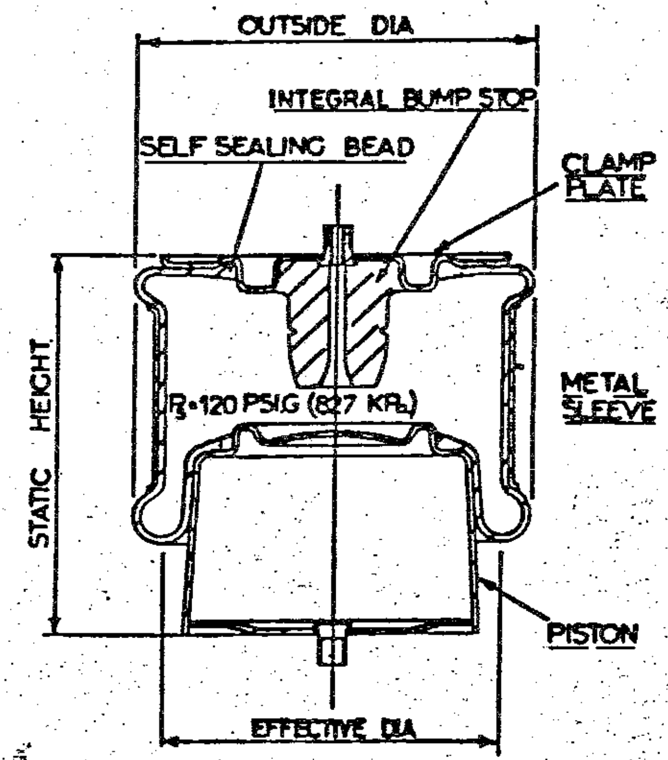
FIG. 2 SPRING STIFFNESS & BOUNCE FREQUENCY v SPRING LOAD.



Typical two convolute bellow air spring FIG. 3



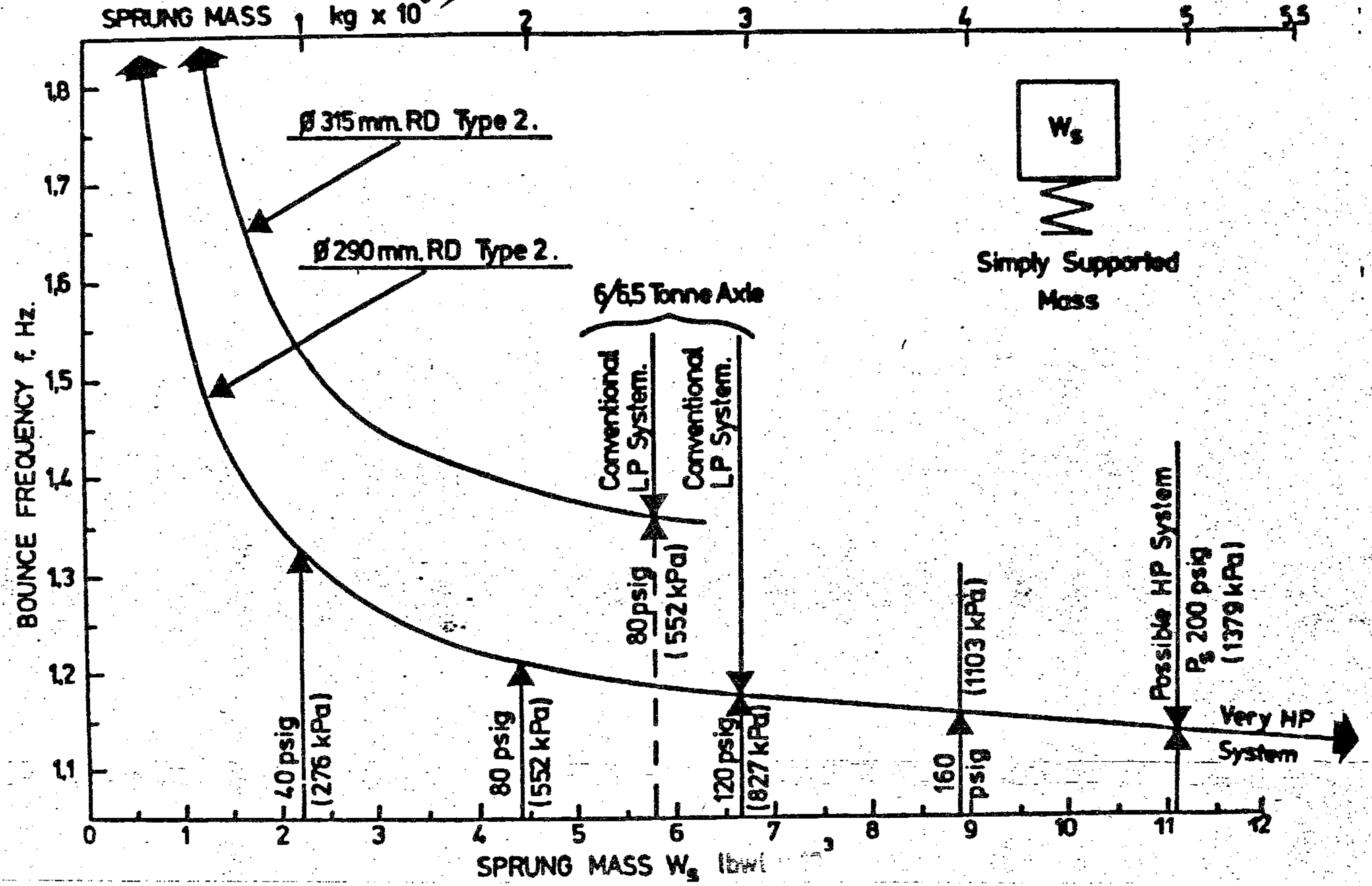
Typical rolling diaphragm air spring assembly FIG. 4

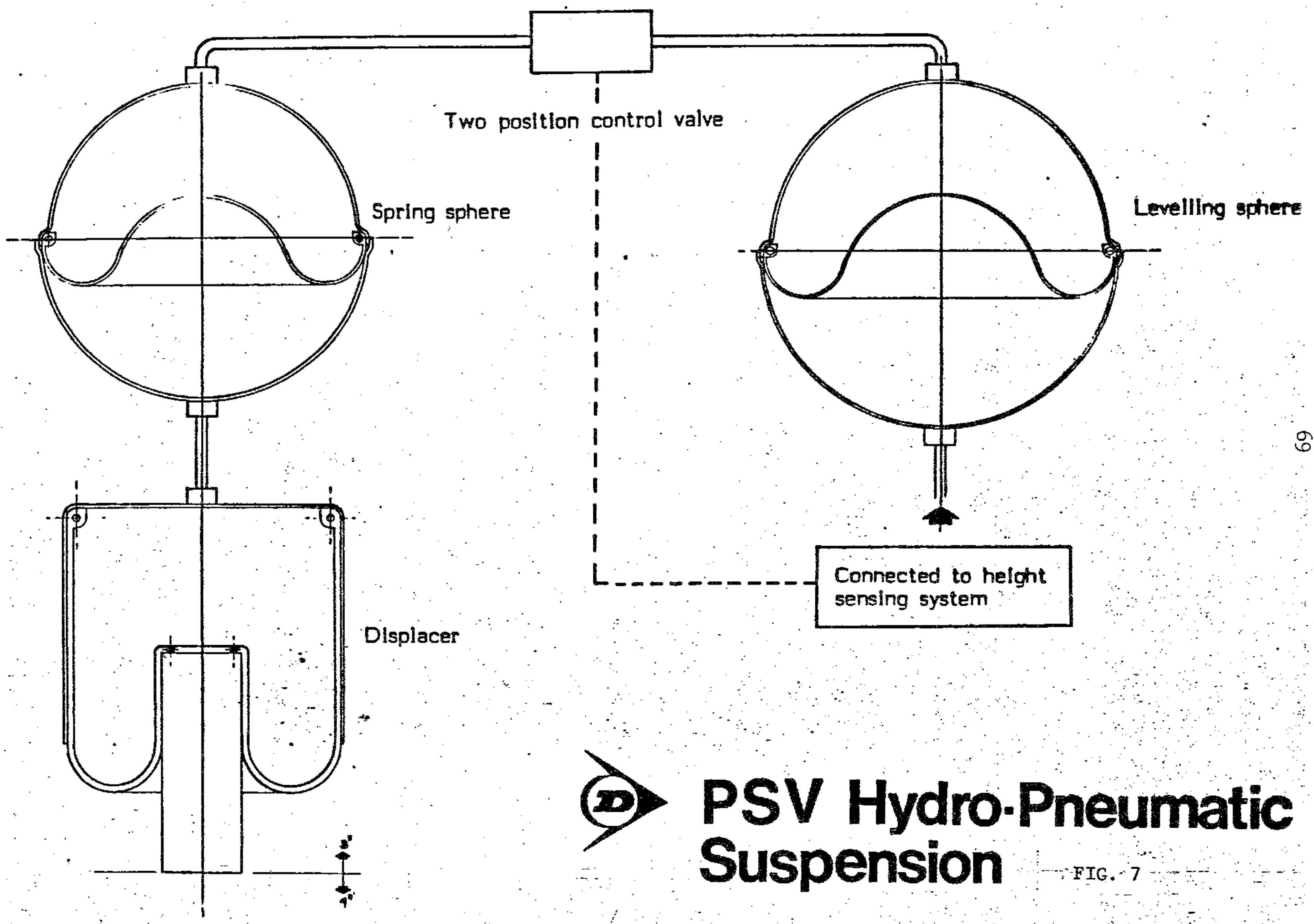


Typical heavy duty rolling diaphragm air spring assembly FIG. 5

Bounce Frequency v Sprung Mass

FIG. 6





PSV Hydro-Pneumatic Suspension

FIG. 7

Hydro Pneumatic System

Component dimensions

FIG. 8

Displacer Unit

Diameter	8"
Installed height	10"
Piston diameter	2"
Effective area	17.5 in^2
Displacement per inch wheel input	18.7 in^2

Rolling lobe to be constrained

Gas Spring Sphere

Sphere diameter	7.7 in
Liquid Volume	115 in^3
Gas Volume	115 in^3
Material Gauge	8 swg

Separator membrane movement:

Bump	1.35 in
Rebound	1.85 in

Levelling Sphere

Sphere Diameter	8.4 in
Volume	310 in^3
Material Gauge	8 swg

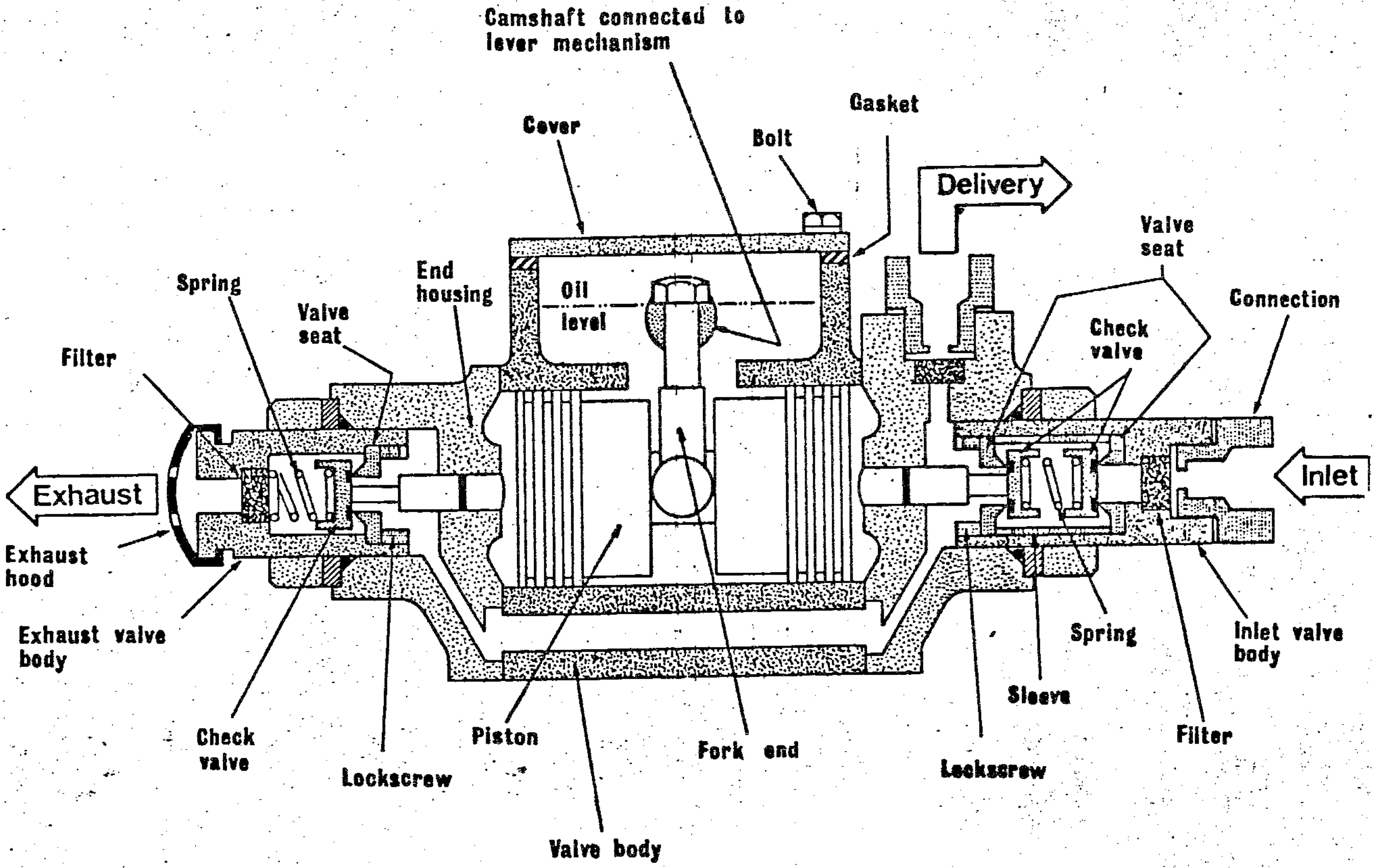


FIG. 9 DELAY LEVELLING VALVE

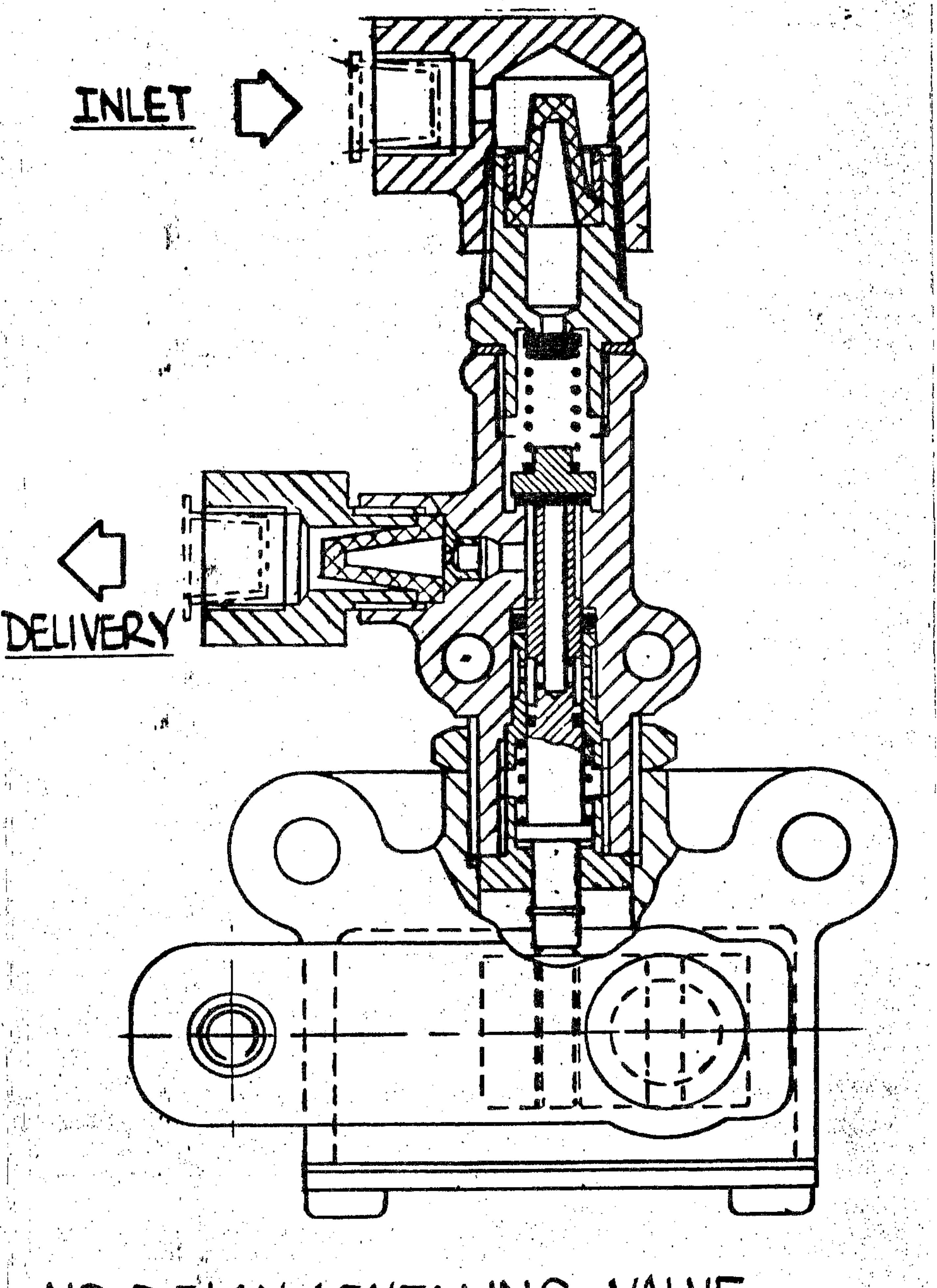


FIG. 10 NO DELAY LEVELLING VALVE

SUMMARY OF AIR CONSUMPTION FOR COACH

		UNLADEN		*FULLY LADEN*	
		URBAN	*MOTORWAY*	*URBAN*	*MOTORWAY*
Average free air used/mile :- Ft^3/mile	*N.D.L.V.*	*0.78*	*0*	*2.78*	*0.53*
	D.L.V.	*0.12*	*0*	*0.65*	*0*
Average flow rate free air :- Ft^3/min.	*N.D.L.V.*	*0.34*	*0*	*1.20*	*0.54*
	D.L.V.	*0.05*	*0*	*0.283*	*0*
Average flow rate to 110 p.s.i. :- Ft^3/min.	*N.D.L.V.*	*0.04*	*0*	*0.14*	*0*
	D.L.V.	*0.006*	*0*	*0.033*	*0*
Air used stop/start :- Ft^3	*N.D.L.V.*	*0.16*		*0.88*	
	D.L.V.	*0.115*		*0.53*	
Charge up time (medium revs)	*N.D.L.V.*	*2 mins 55 secs*		*3 mins 29 secs*	
	D.L.V.	*1 min 24 secs*		*1 min 42 secs*	

TABLE 1

GENERAL SYNOPSIS OF RESULTS

N.D.L.V.	D.L.V.	COMMENTS
Unladen Versus	Unladen	D.L.V. more economical
Fully Laden Versus	Fully Laden	D.L.V. more economical
	Unladen V Fully Laden	More air used in laden condition
Unladen V Fully Laden		More air used in laden condition
	Levelling Capability Unladen	± 16mm approx.
	Levelling Capability Fully Laden	± 42mm approx.
Levelling Capability Unladen		± 8mm approx.
Levelling Capability Fully Laden		± 8mm approx.

TABLE 2

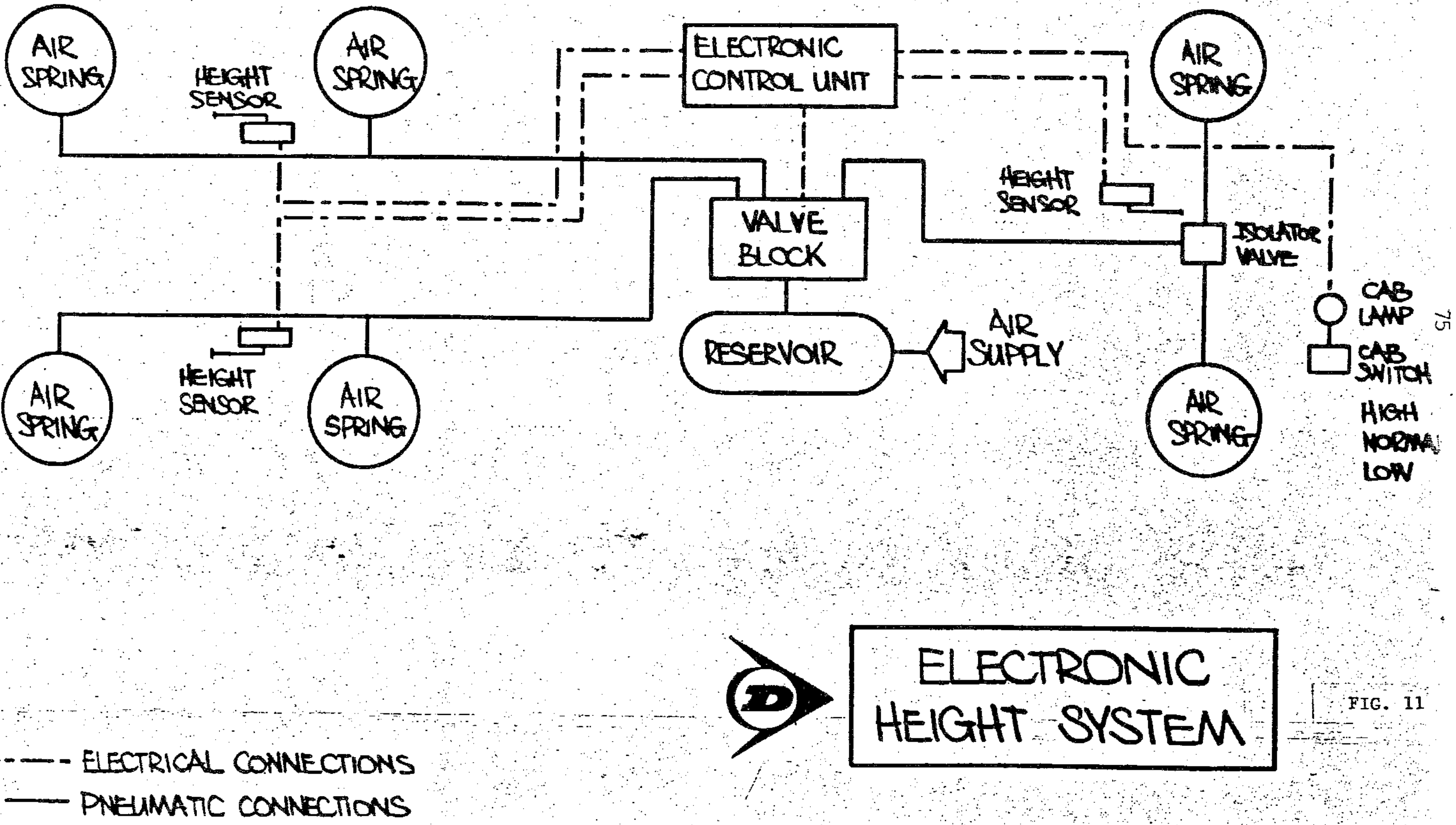
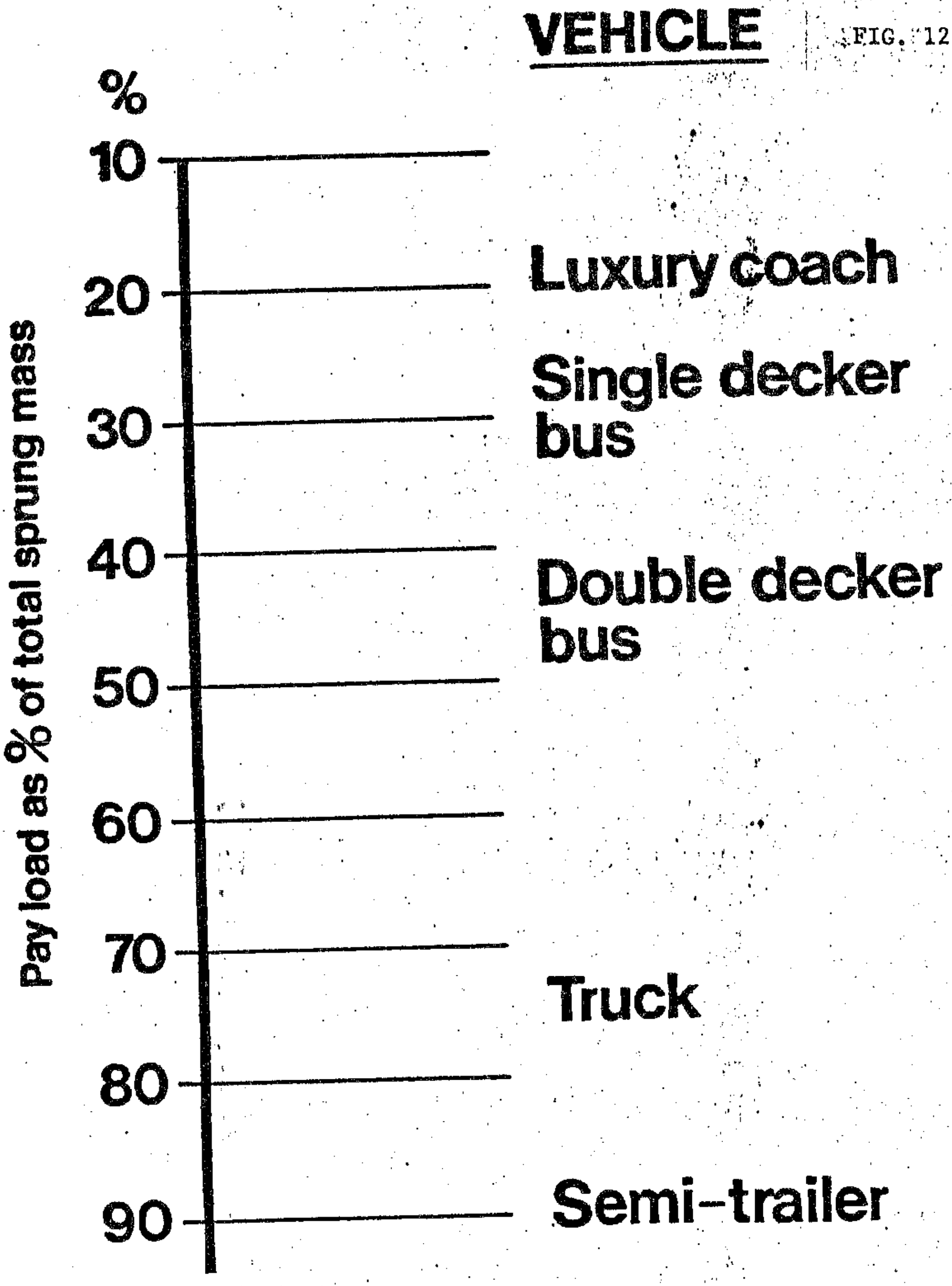

AIR SPRING
HEIGHT SENSOR
AIR SPRING
ELECTRONIC CONTROL UNIT
AIR SPRING
HEIGHT SENSOR
ISOLATOR VALVE
CAB LAMP
CAB SWITCH
HIGH
NORMAL
LOW
VALVE BLOCK
RESERVOIR
AIR SUPPLY
AIR SPRING
HEIGHT SENSOR
AIR SPRING
AIR SPRING
ELECTRONIC HEIGHT SYSTEM
ELECTRICAL CONNECTIONS
PNEUMATIC CONNECTIONS

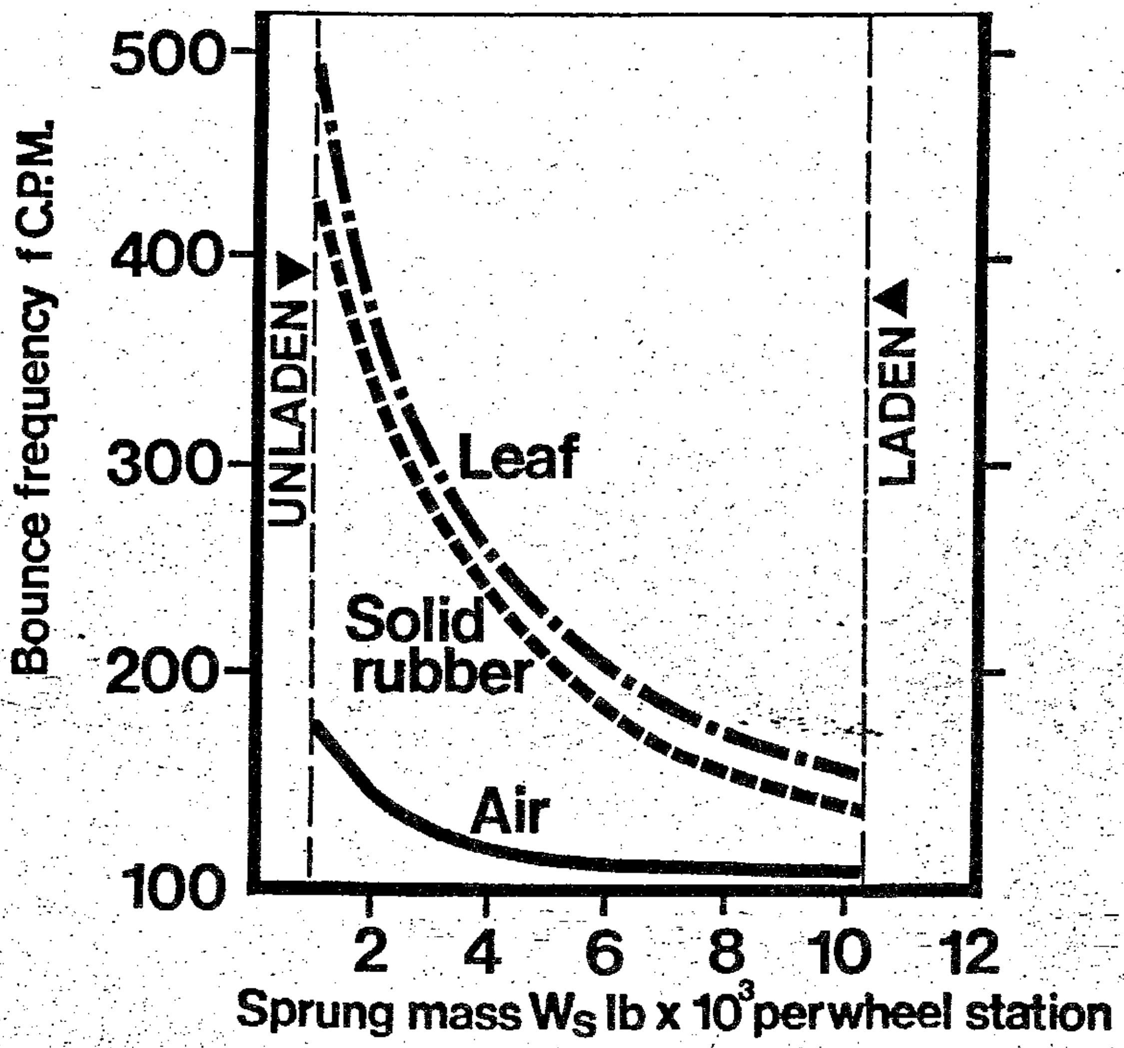
FIG. 11

FIG. 12


VEHICLE
%
Pay load as % of total sprung mass
10
20
30
40
50
60
70
80
90
Luxury coach
Single decker bus
Double decker bus
Truck
Semi-trailer

Leaf, Rubber and Air Suspension Compared

FIG. 13



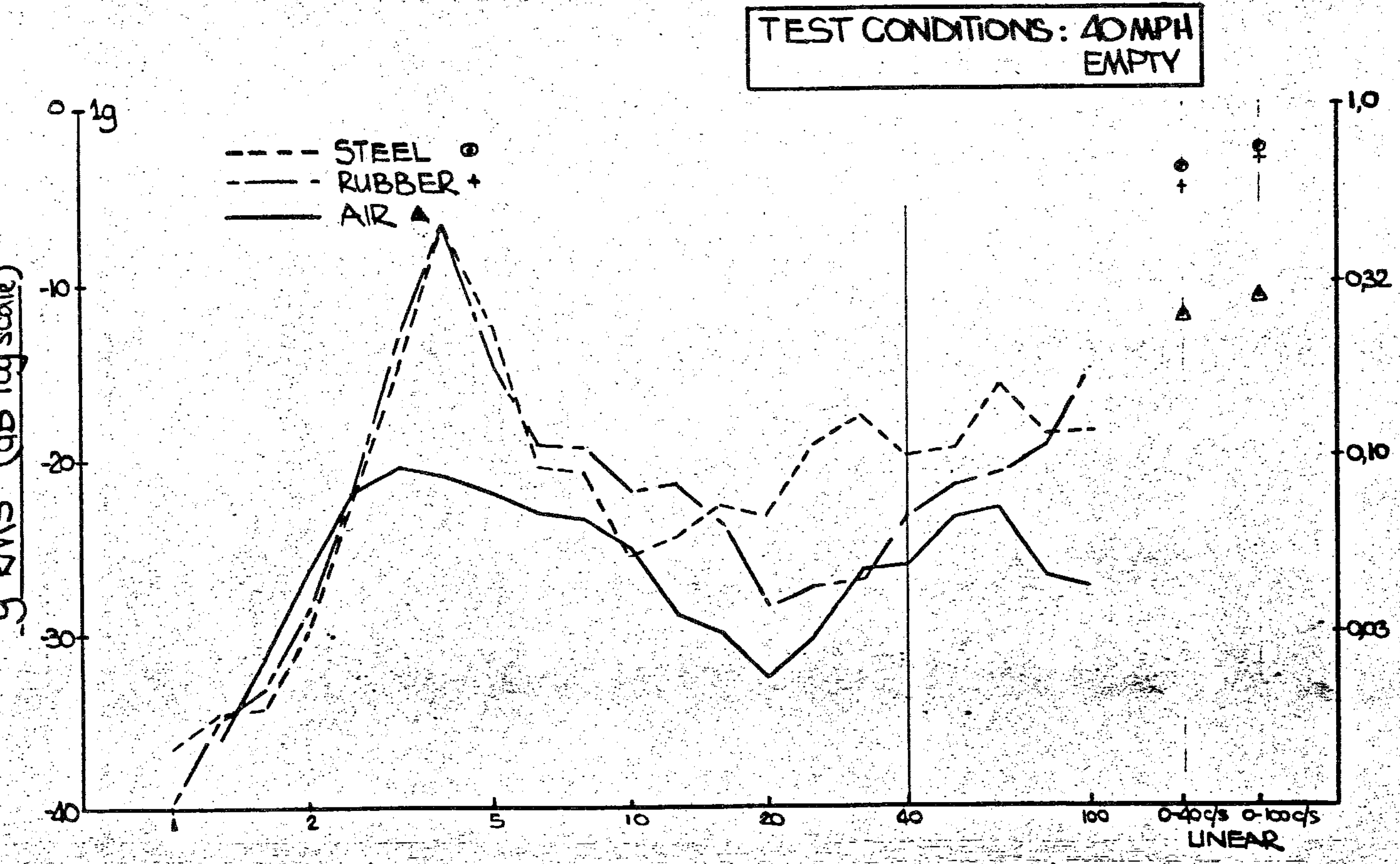


FIG. 14

1/3 OCTAVE CENTRE FREQUENCY c/S

ABOVE TRAILER AXLE

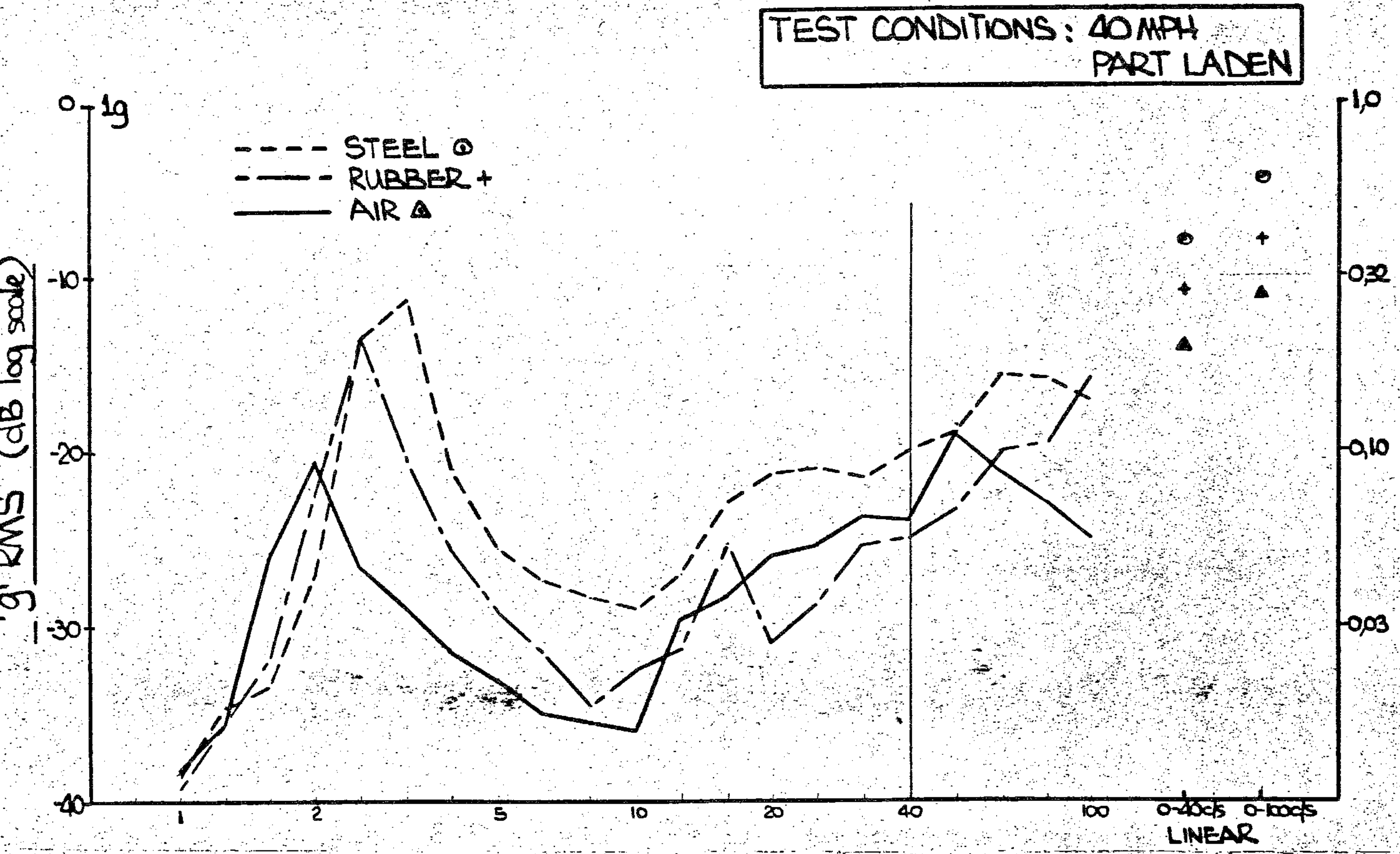


FIG. 15

1/3 OCTAVE CENTRE FREQUENCY c/s

ABOVE TRAILER AXLE

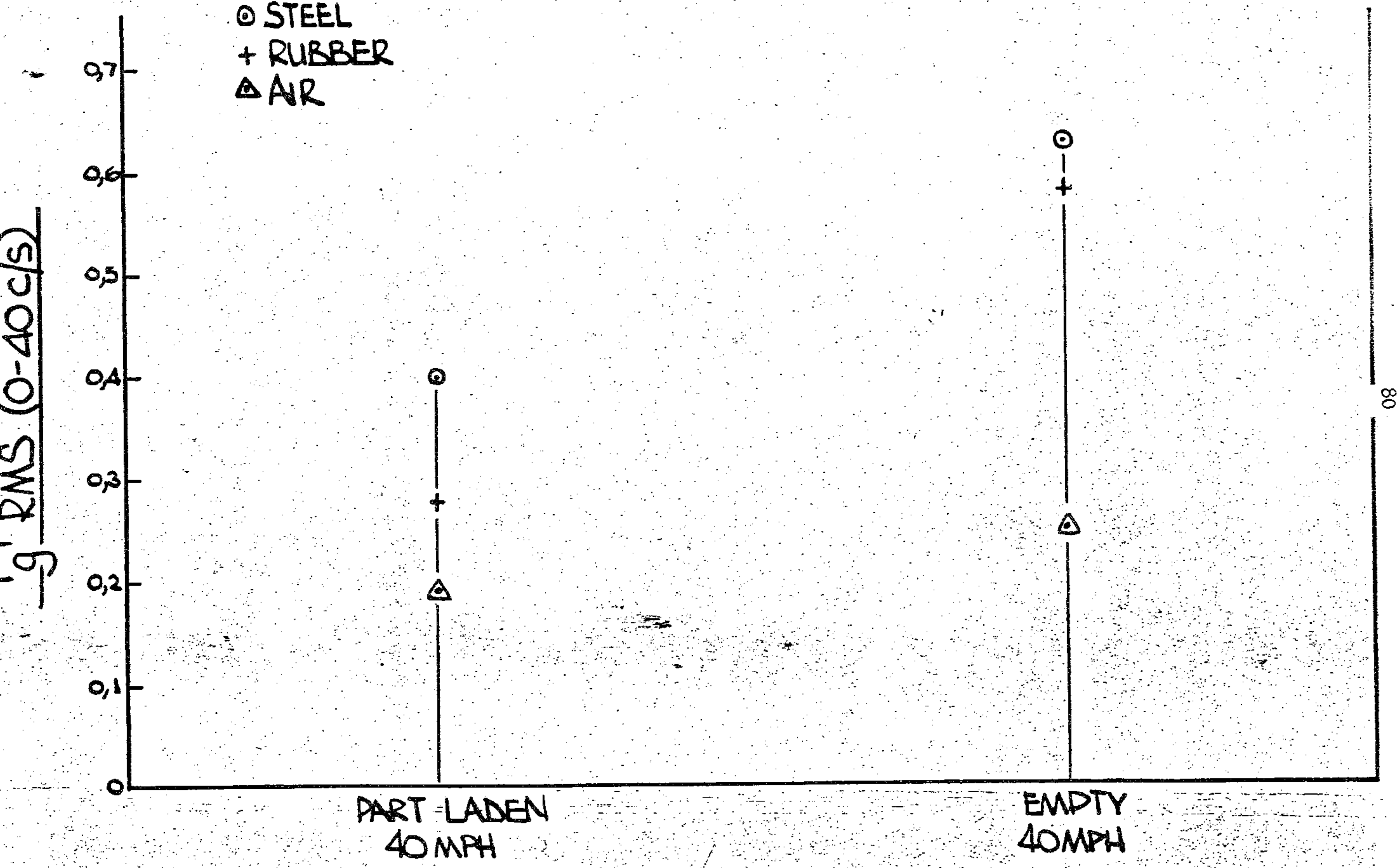


FIG. 16 VERTICAL ACCELERATIONS ABOVE TRAILER AXLE, RMS'g'

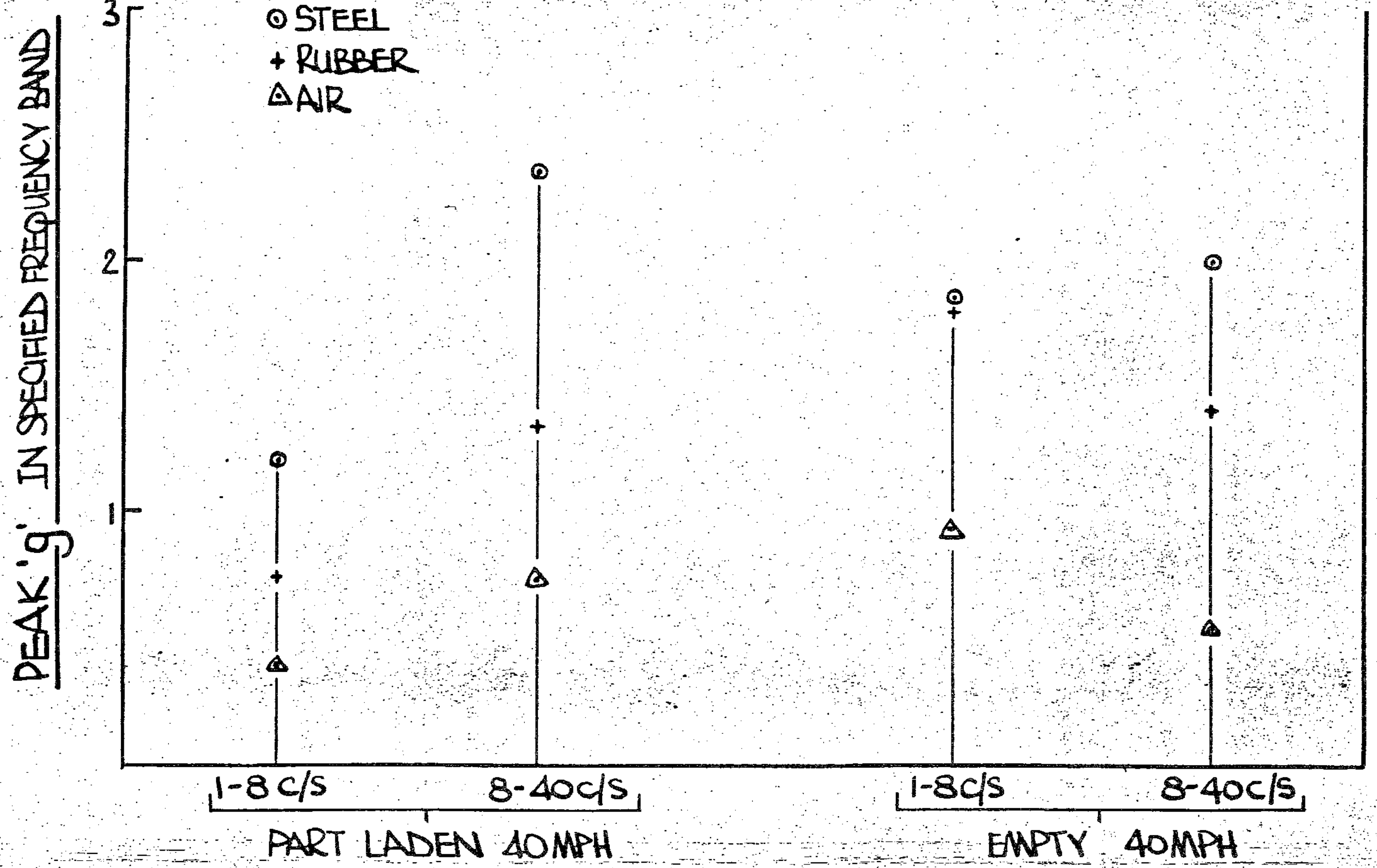
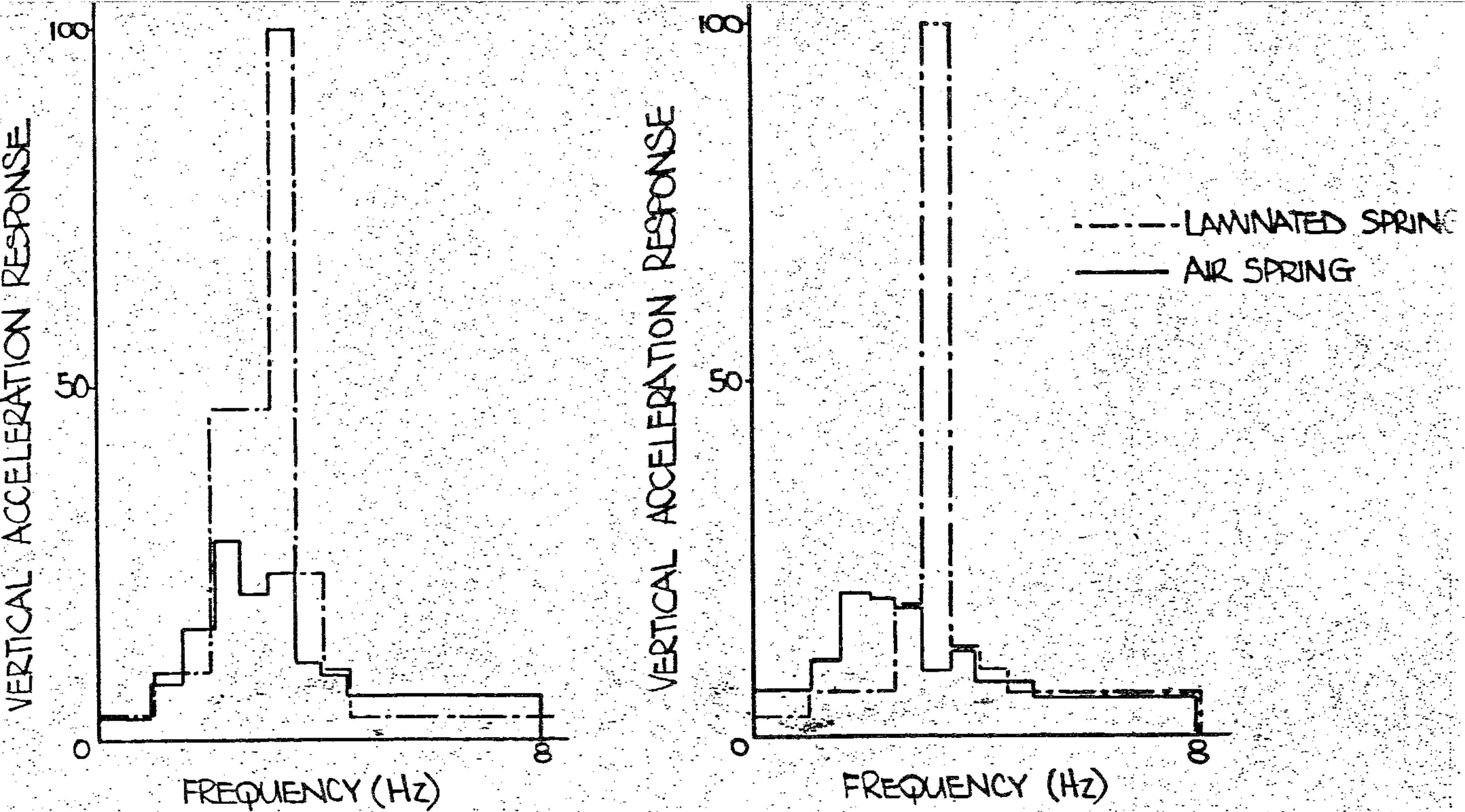


FIG. 17 VERTICAL ACCELERATIONS ABOVE TRAILER AXLE - PEAK 'g'



FRONT

REAR

SUSPENSION RIDE COMPARISON - UPPER DECK

ASPHALT TOWN ROAD

FIG. 18

APPENDIX

A	Effective area
dA	Incremental change in area
F	Force
F_a	Adiabatic force
$\frac{dF}{dh}$	Stiffness
$\frac{dF}{dh}_{ISO}$	Isothermal (static) stiffness
$\frac{dF}{dh}_{ADIAB}$	Adiabatic (dynamic) stiffness
f	Bounce frequency
h	Air spring height
dh	Incremental change in height
n	Polytropic constant
p	Gauge pressure
p_a	Adiabatic pressure
p_{abs}	Absolute pressure
p_{atm}	Atmospheric pressure
p_s	Air spring pressure
dp	Incremental change in pressure
V	Volume
dV	Incremental change in volume
W_s	Sprung mass
$\frac{dA}{dh}$	Rate of change in area with height
$\frac{dp}{dh}$	Rate of change in pressure with height
$\frac{dV}{dh}$	Rate of change in volume with height

SESSION C

P. Stone

At this moment in time it hasn't been fully decided yet because of the EEC regulations which are going to be changed. The overall EEC loadings. It looks as though Belgium will still go higher than the EEC allowance if you fit air suspension.

What is the allowance?

P. Stone

The allowance will go from 38 to 40 in general thoughout the EEC with the exception of the UK and that is being debated by the EEC Parliament at the moment. Belgium will go 40 to 44 I think is the figure that they were quoting.

J. Wilkinson

Thanks Paul, next question.

P. Sweatman

About the height control valve in air suspension. When tilt testing for stability of a vehicle we have looked at how long it takes for a height control valve to come into action on the downhill side on the tilt deck. It can take 20 to 30 seconds for that pressure to build up. Which type of valve is that?

P. Stone

That is the delay type valve which is reacting there. But, referring back to the bus industry, some bus manufacturers have had severe problems in the tilt test, certainly in the EEC. Where they are concerned about this they have fitted tilt switches with mercury roll switches which as soon as the tilt reaches a certain angle automatically throwing air on that side and the levelling valve comes in later on. So yes there are certain PSVs in Europe which have problems and a tilt switch is fitted to get out of that particular problem. It is a functional delay valve.