

Archive of SID

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[ ]

(shock

absorber)

(Isolator)

[ ]

bounce

[ ] Haddow Brach

[ ] Singh Kim

[ ] Nakhaie Golnaraghi

[ ] Geisberger

[ ] Adiguna

[ ] Lu Shangguan

Geisberger

ADINA

[ ]

[ ]

[ ]

Geisberger

ANSYS/MATLAB/Simulink

[ ]

[ ]

ANSYS

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(Ethylene glycol)

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Geisberger .

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<sup>1</sup> Inertia Track  
<sup>2</sup> Decoupler  
<sup>3</sup> Damping channel

$$\begin{aligned}
 & \left( \begin{array}{c} \dot{X}(t) \\ \dot{P}_2(t) \\ \dot{P}_1(t) \\ \dot{Q}_i(t) \\ \dot{Q}_d(t) \end{array} \right) = \left( \begin{array}{ccc} -\frac{1}{C_1} & 0 & 0 \\ 0 & -\frac{1}{C_2} & 0 \\ 0 & 0 & -\frac{1}{C_1} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{array} \right) \left( \begin{array}{c} X(t) \\ P_2(t) \\ P_1(t) \\ Q_i(t) \\ Q_d(t) \end{array} \right) + \left( \begin{array}{c} \frac{b_r}{C_1} \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right) \dot{X}_T(t) + \left( \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array} \right) \dot{Q}_d(t) \\
 & \left( \begin{array}{c} \dot{P}_1 - \dot{P}_2 \\ \dot{Q}_i \\ \dot{Q}_d \end{array} \right) = \left( \begin{array}{ccc} I_d & R_d & R_{add} \\ 0 & R_i & 0 \\ 0 & 0 & R_i \end{array} \right) \left( \begin{array}{c} Q_d \\ Q_i \\ Q_d \end{array} \right) + \left( \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right) \dot{Q}_d(t) + \left( \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right) \dot{Q}_i(t) \\
 & \left( \begin{array}{c} \dot{P}_1 - \dot{P}_2 \\ \dot{Q}_i \\ \dot{Q}_d \end{array} \right) = \left( \begin{array}{ccc} I_d & R_d & R_{add} \\ 0 & R_i & 0 \\ 0 & 0 & R_i \end{array} \right) \left( \begin{array}{c} Q_d \\ Q_i \\ Q_d \end{array} \right) + \left( \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right) \dot{Q}_d(t) + \left( \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right) \dot{Q}_i(t)
 \end{aligned}$$

<sup>1</sup> Volumetric Compliance

<sup>2</sup> Lumped Parameter

$$P_1, P_2, Q_i, Q_d$$

$A_{d\_fnc}$

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[ ]

$$F_T = k_r X + b_r \dot{X} + (A_p - A_{d\_fnc})(P_1 - P_2) + A_p P_2 + A_d (R_d + R_d |Q_d|) Q_d \quad ( )$$

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$(P_1 - P_2)$

$(\partial P / \partial X)$

$\partial P / \partial X$

$(\partial P / \partial X)$

$(Q_i \ Q_d)$

$(P_1 - P_2)$

$Q_i \quad Q_d$

X

-  $(dX/dt)$

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$$v_i = \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{Bmatrix} v_x(X, Y) \\ 0 \\ 0 \end{Bmatrix} \quad (1)$$

$$\dot{\rho} + \rho v_{i,i} = 0 \quad (2)$$

$$\dot{\rho} = \frac{\partial \rho}{\partial t} + v_i \rho_{,i} \quad (3)$$

$$\dot{\rho} = 0 \quad (4)$$

$$v_{i,i} = \frac{\partial v_x}{\partial X} + \frac{\partial v_y}{\partial Y} + \frac{\partial v_z}{\partial Z} = 0 \quad (5)$$

$$\frac{\partial v_x}{\partial X} = 0 \quad (6)$$

$$v_i = \begin{cases} v_x(Y) \\ 0 \\ 0 \end{cases} \quad ( )$$

$$D_{ij} = \frac{1}{2}(v_{i,j} + v_{j,i}) \quad ( )$$

$$D = \begin{bmatrix} 0 & \frac{1}{2} \frac{\partial v_x}{\partial Y} & 0 \\ \frac{1}{2} \frac{\partial v_x}{\partial Y} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad ( )$$

$$D_{kk} = 0$$

$$\sigma_{ij} = -P\delta_{ij} + \lambda\delta_{ij}D_{kk} + 2\mu D_{ij} \quad ( )$$

$$\lambda, \mu, P, \sigma_{ij}, \delta_{ij}, D_{kk} = 0$$

$$\sigma_{ij} = -P\delta_{ij} + 2\mu D_{ij} = \begin{bmatrix} -3P & \mu \frac{\partial v_x}{\partial Y} & 0 \\ \mu \frac{\partial v_x}{\partial Y} & -3P & 0 \\ 0 & 0 & -3P \end{bmatrix} \quad ( )$$

$$\sigma_{ij,j} + \rho b_i = \rho(v_{i,t} + v_j v_{i,j}) \quad ( )$$

$$b_i$$

$$b_i = (g, 0, 0) \quad ( )$$

$$-3 \frac{\partial P}{\partial X} + \mu \frac{\partial^2 v_x}{\partial Y^2} + \rho g = \rho v_{x,t} \quad ( )$$

$$\mu \frac{\partial^2 v_x}{\partial Y^2} - 3 \frac{\partial P}{\partial Y} = 0 \quad ( )$$

$$\frac{\partial P}{\partial Z} = 0 \quad ( )$$



$$v = v(X, Y, t) \quad (1)$$

$$P = P(X, Y, t) \quad (2)$$

$$v(X, 0, t) = 0 \quad (3)$$

$$v(X, a, t) = \dot{X}_d(t) \quad (4)$$

$$P(0, Y, t) = P_1 \quad (5)$$

$$P(t_d, Y, t) = P_2 \quad (6)$$

$$v(X, Y, 0) = v_0 \quad (7)$$

$$\frac{\partial P}{\partial Y} = 0 \quad (8)$$

$$-3 \frac{\partial P}{\partial X} + \rho g = \rho v_{x,t} \quad (9)$$

$$\frac{\partial^2 v}{\partial Y^2} = 0 \quad (10)$$

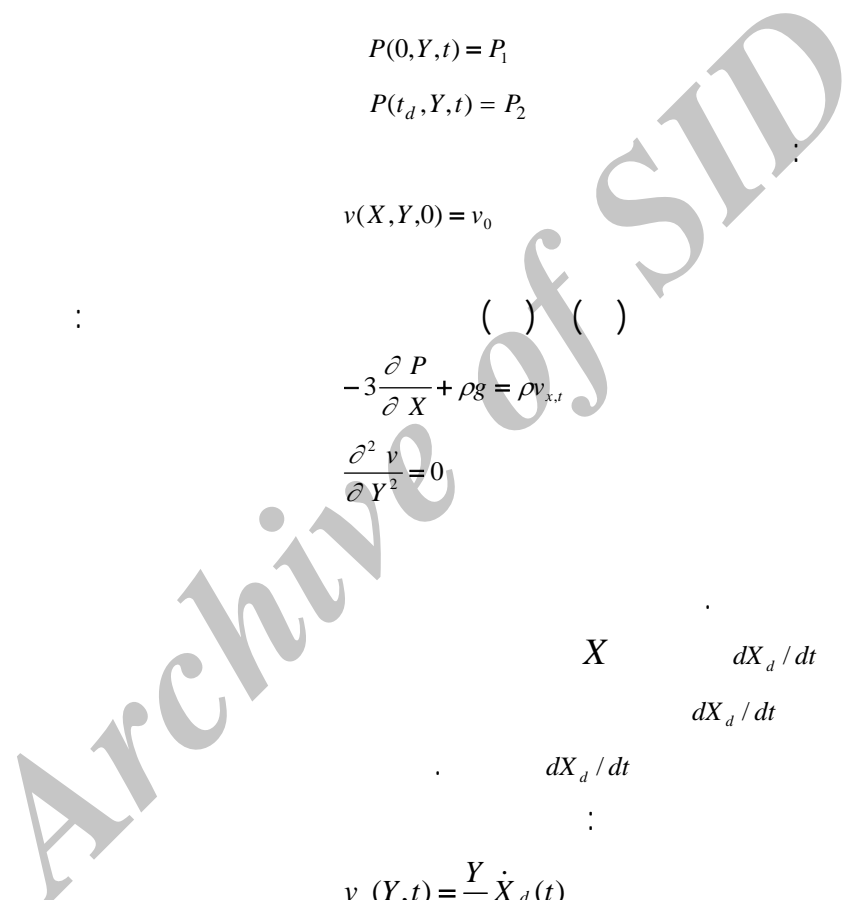
$$X \quad dX_d / dt \quad (11)$$

$$dX_d / dt \quad (12)$$

$$v_x(Y, t) = \frac{Y}{a} \dot{X}_d(t) \quad (13)$$

$$\frac{\partial v_x(Y, t)}{\partial t} = \frac{Y}{a} \ddot{X}_d(t) \quad (14)$$

$$-3 \frac{\partial P(x, t)}{\partial X} + \rho g = \rho \frac{Y}{a} \ddot{X}_d(t) \quad (15)$$



$$P_1(t)$$

$$P(X, t) = \frac{1}{3} \rho g X - \rho \frac{Y}{3a} \ddot{X}_d(t) \cdot X + P_1(t) \quad ( )$$

:

$$Q_d(t) = \frac{\pi D_{av,d}}{a} \dot{X}_d(t) \int_{y=0}^{y=a} y dy \Rightarrow$$

$$Q_d(t) = \frac{a\pi D_d}{2} \dot{X}_d(t) \quad ( )$$

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$D_d$

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$$v_i = \begin{matrix} \left[ \begin{matrix} v_x \\ v_y \\ v_z \end{matrix} \right] \\ t \quad r \end{matrix} = \begin{matrix} \left[ \begin{matrix} v_x(r, \theta, t) \\ 0 \\ 0 \end{matrix} \right] \\ \end{matrix} \quad ( )$$

:

$$v_x(r, t) = -\frac{R_i^2 - r^2}{4\mu} \frac{\partial}{\partial x} (P + \gamma h) \quad ( )$$

:

<sup>1</sup> Hegen-Poisealle

$$\partial h / \partial x = 0 \quad ( )$$

:

$$Q_i = \int_{r=0}^{r=R_i} - \left( \frac{R_i^2 - r^2}{4\mu} \right) \left( \frac{\partial P(x,t)}{\partial X} \right) (2\pi r dr) \quad ( )$$

$$= - \frac{\pi R_i^4}{8\mu} \frac{\partial P(x,t)}{\partial X}$$

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:

$$Q_i = - \frac{\pi R_i^4}{8\mu} \frac{P_2(t) - P_1(t)}{l_i} \quad ( )$$

 $Q_i$ 

:

$$-3 \frac{\partial P}{\partial X} = \rho \left( - \frac{R_i^2 - r^2}{4\mu} \right) \frac{\partial^2 P}{\partial X \partial t} \quad ( )$$

$$\partial P / \partial X = \eta$$

Least-square

(W)

ANSYS

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Least-square

ANSYS

Mooney-Rivlin

$$I_1, I_2, I_3$$

$$\lambda_1, \lambda_2, \lambda_3$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_1^2 \lambda_3^2 \quad ( )$$

$$I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2$$

$$( ) \lambda_1, \lambda_2, \lambda_3$$

(C<sub>ij</sub>)

$$\det[C_{ij} - \lambda_p^2 \delta_{ij}] = 0 \quad ( )$$

:[ ]

Mooney-Rivlin

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2$$

$$+ C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2 - 3)^2 + C_{30}(I_2 - 3)^2 \quad ( )$$

$$+ C_{21}(I_1 - 3)^2(I_2 - 3) + C_{12}(I_1 - 3)(I_2 - 3)^2 + C_{03}(I_2 - 3)^3 + \frac{1}{d}(J - 1)^2$$

$$C_{10}, C_{01}, C_{20}, C_{11}, C_{02}, C_{30}, C_{21}, C_{12}, C_{03}, d$$

$$\mu = 2(C_{10} + C_{01})$$

ANSYS

Mooney-Rivlin

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ANSYS

$$b_r \quad k_r$$

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Geisberger

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$$k_r = k_r(\omega, X, F_p) \quad ( )$$

$$b_r = b_r(\omega, X, F_p) \quad ( )$$

$$F_p \quad X \quad \omega$$

$$k_v^* = k_v(1 + \eta_v i) \quad ( )$$

$$k_b^* = k_b(1 + \eta_b i) \quad ( )$$

$$k_h^* = k_h(1 + \eta_h i) \quad ( )$$

Bulge

-

-

$\eta_h \quad \eta_b \quad \eta_v$

loss factor

ANSYS

Loss

( )

Mooney-Rivlin

Factor

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Simulink

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<sup>1</sup> Voigt

<sup>2</sup> Axisymmetric

$(R_i, R_d)$

$(A_p)$   $(C_1, C_2)$   
 $b_r$   $k_r$  [ ]

( )

:[ ]

$$A_{d\_fnc} = \frac{1}{\pi} A_d \left( \frac{\pi}{2} - \arctan \left( \frac{(2/\pi) X_d \arctan((P_1 - P_2)/P_0 - X_{d\_max})}{X_1} \right) \right) \quad ( )$$

$(X_d)$

( )  $(\pm X_{d\_max})$

$X_1$   $P_0$

[ ]

Simulink ( ) ( ) ( ) ( ) ( ) ANSYS

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( ) 50 0 2mm 0.1mm  
 ( ) 500 250 ( ) 250 50  
 50Hz 0.1mm ( )

( )

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$(Q_d)$

( ) ( )

= 0)

<sup>1</sup> Soft

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0.1mm

6Hz

2mm

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50Hz

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2mm

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3000N

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 [ ] Singh Kim . ( [ ] )

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MTS

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831.5

Strain-gage loadcell

Accelerometer Compensator

Piezoelectric load washer

( )

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( )

( ) ( )

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( ) ( )

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( )

( $R_d$ ,  $R_i$ )

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( ) ( )

( )

( ) ( )

[ ] Singh Kim

(  $f_{K_{min}}$  )

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## MATLAB-Simulink

- [1] Brach, R. M., and Haddow, A., "On The Dynamic Response of Hydraulic Engine Mounts", SAE Technical Paper Series 931321, pp. 463-474, (1993).
- [2] Kim, G., and Singh, R., "A Study of Passive and Adaptive Hydraulic Engine Mount Systems", Journal of Sound and Vibration, Vol. 179, pp. 427-453, (1995).
- [3] Golnaraghi, M. F., and Nakhaie, R., "Development and Analysis of A Simplified Nonlinear Model of a Hydraulic Engine Mount", Journal of Vibration and Control, Vol. 7, pp. 495-526, (2001).
- [4] Geisberger, A., Khajepour, A., and Golnaraghi, M. F., "Non-linear Modeling of Hydraulic Engine Mounts: Theory and Experiment", Journal of Sound and Vibration, Vol. 249, pp. 371-397, (2002).
- [5] Adiguna, H., Tiwari, M., Singh, R., and Hovat, D., "Transient Response of a Hydraulic Engine Mount", Journal of Sound and Vibration, Vol. 268, pp. 217-248, (2003).
- [6] Shangguan, W. B., and Lu, Z. H., "Modeling of a Hydraulic Engine Mount with Fluid-Structure Interaction Finite Element Analysis", Journal of Sound and Vibration, Vol. 275, pp. 193-221, (2004).

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$m^2$  : A  
N/(m.s) : b

$m^4.s^2/kg$  : C

m : D

N : F

$m/s^2$  , : g

m , : h

$kg/m^4$  , : I

N/m , : k

Pa , : P

$m^3/s$  , : Q

$N.s/m^5$  , : R

s , : t

m/s , : v

: X

: Y

$kg/m^3$  :  $\rho$

: l

: 2

: d

: i

: r

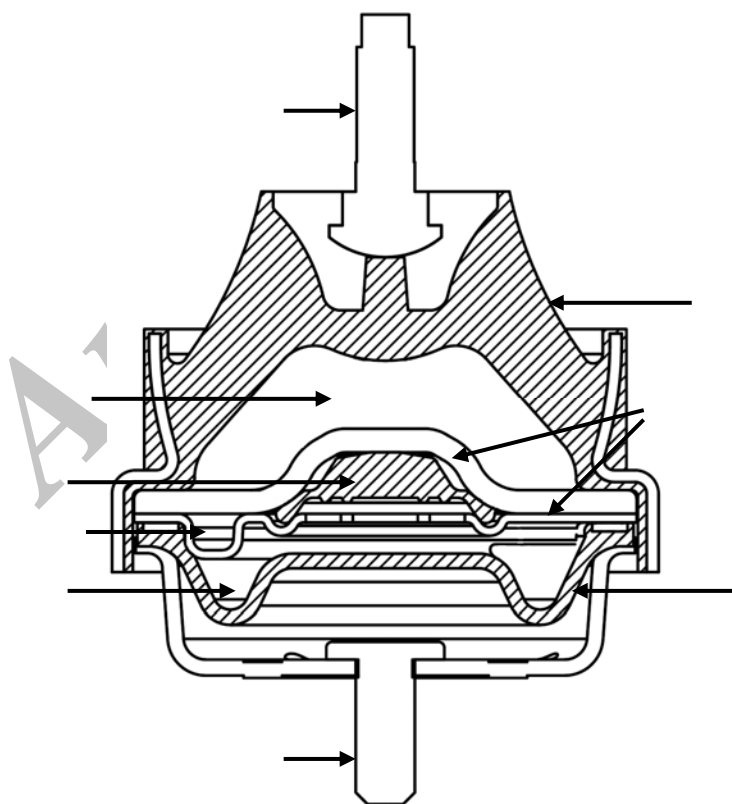
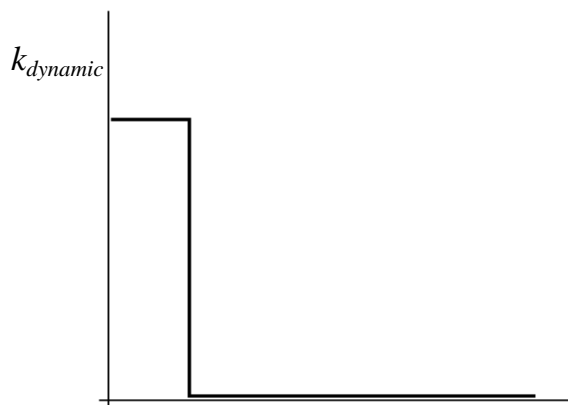
Ogden (3 <sup>rd</sup> order)	Neo-Hookean	Arruda-Boyce
$\mu_1 = 27.698$ $\alpha_1 = 53.786$ $\mu_2 = \mu_3 = \mu_1$ $\alpha_2 = \alpha_3 = \alpha_1$ $d_1 = d_2 = d_3 = 0$	$\mu = 811320.633$ $d = 0$	$\mu = 1.11327$ $\lambda_L = -0.184$ $d = 0$
Gent	Blatz-Ko	Mooney-Rivlin (2 parameter)
$\mu = 811356.017$ $J_m = -7148.15$ $d = 0$	$\mu = 646882.97$	$C_{10} = 552e6$ $C_{01} = 138e6$

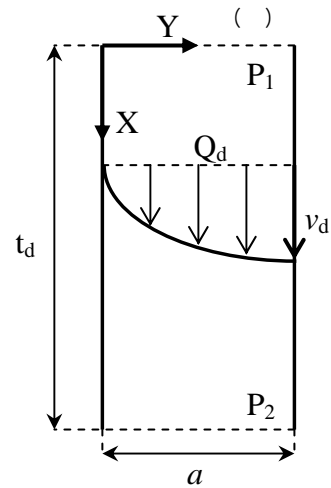
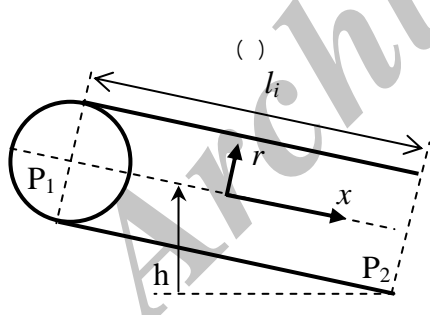
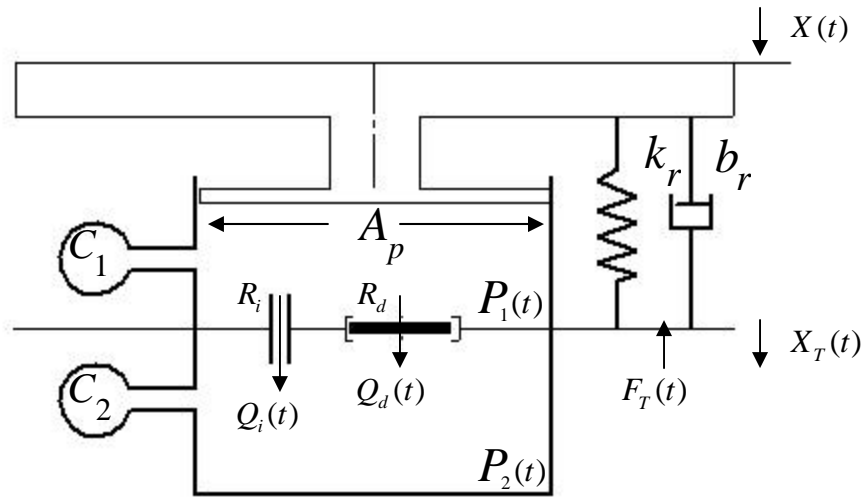
ANSYS

E (Mpa)	Poisson ratio	C <sub>10</sub> (Mpa)	C <sub>01</sub> (Mpa)	Density (kg/m3)	Shear modulus (kgf/cm2)	Element type
/	/	/	/	/	/	PLANE182 (2D-8Node)
		Loss Factor	(N/m)			
		/				
		/				
		/			bulge	

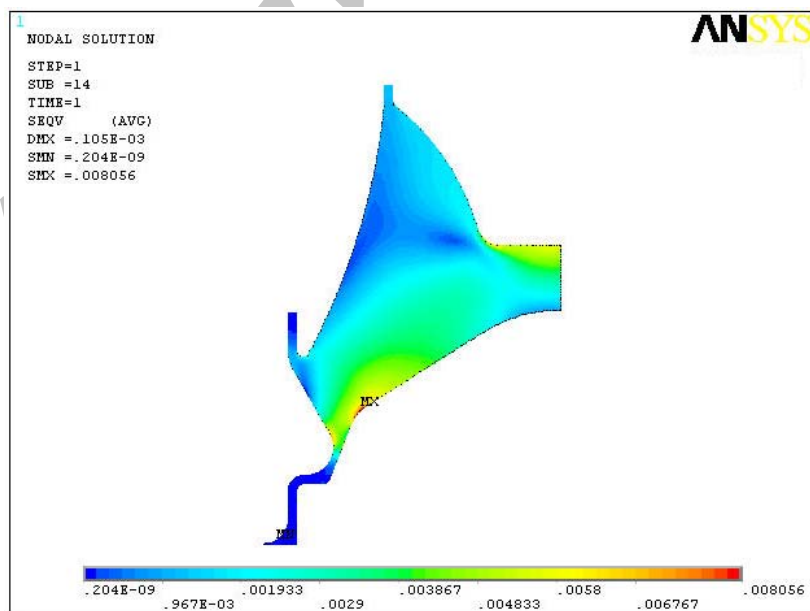
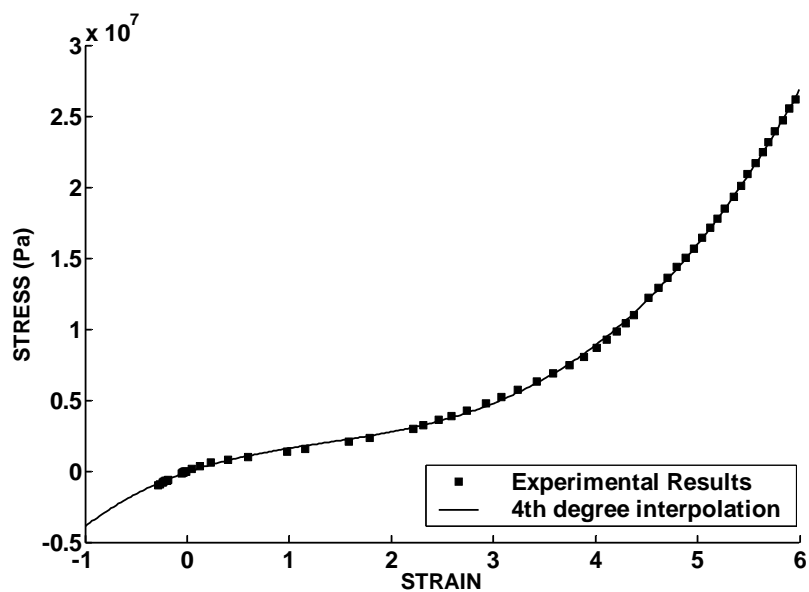
[ ]

$K_r = 225(N/mm)$	$R_i = 10.5 \times 10^{-5}(kg.mm^4/s)$	$C_1 = 3.0 \times 10^4(mm^5/N)$
$b_r = 0.1 \times 10^3(kg/s)$	$R_i' = 0.0$	$C_2 = 2.6 \times 10^6(mm^5/N)$
$A_p = 2500(mm^2)$	$R_d = 11.7 \times 10^{-6}(kg.mm^4/s)$	$I_i = 3.8 \times 10^{-6}(kg/mm^4)$
$A_d = 660(mm^2)$	$R_d' = 0.0$	$I_d = 7.5 \times 10^{-8}(kg/mm^4)$

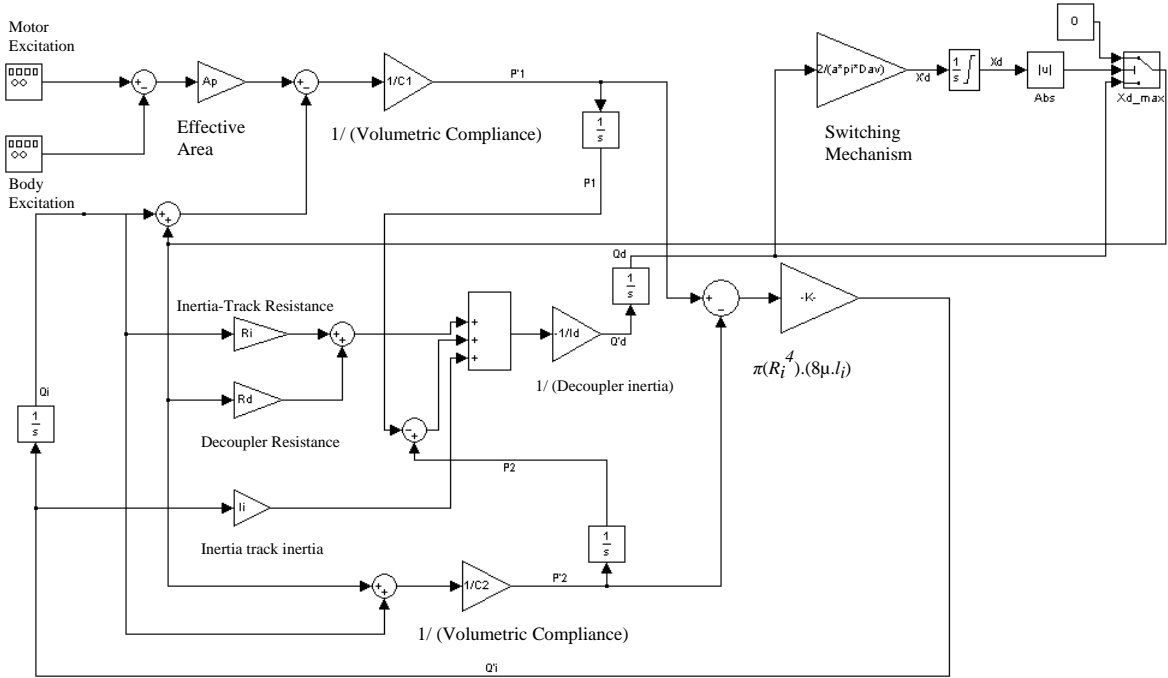




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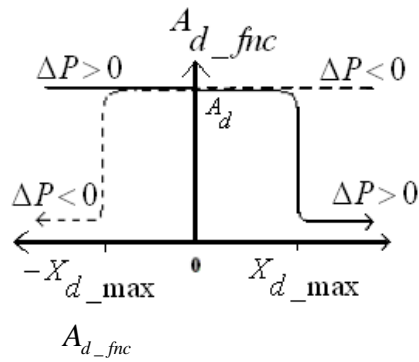


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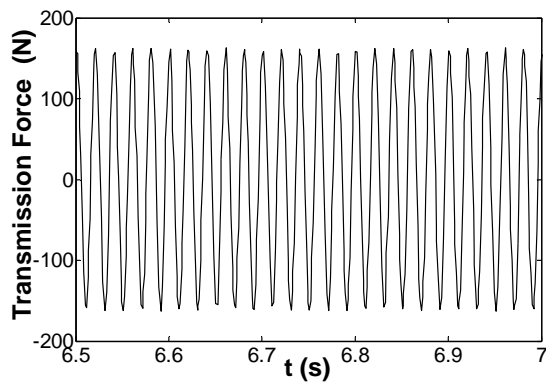
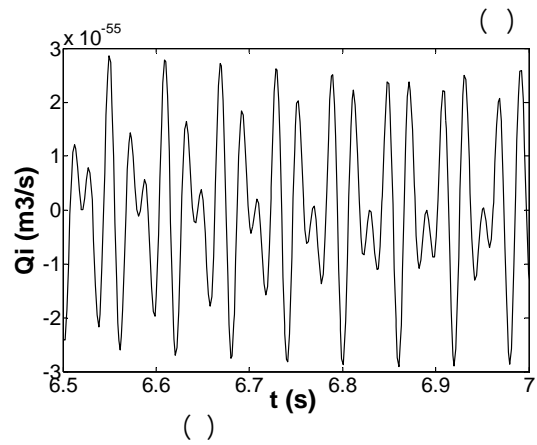
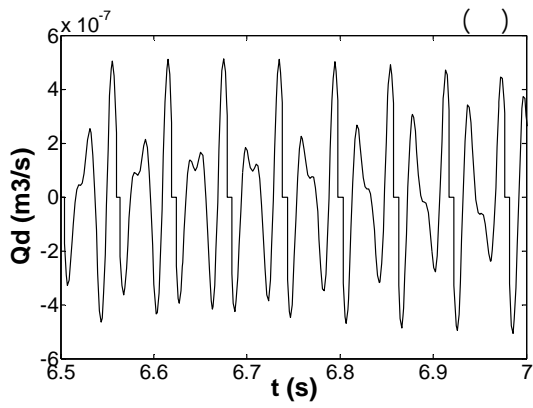


Simulink

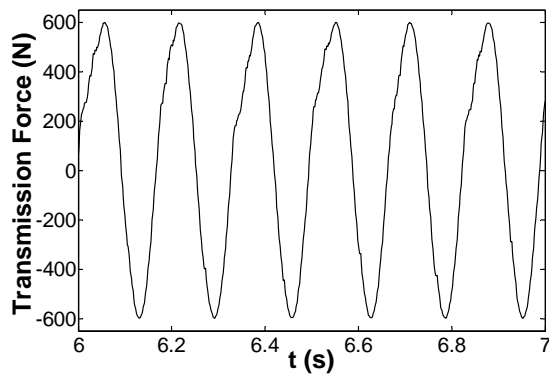
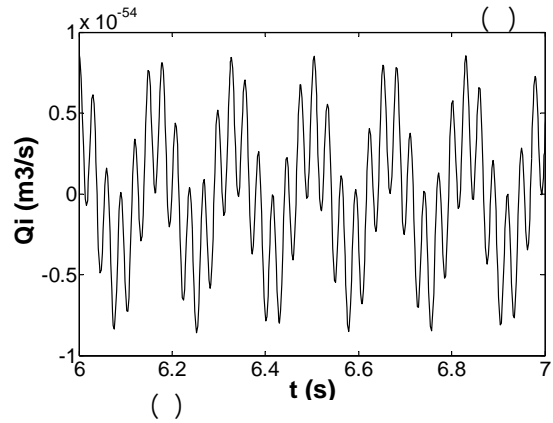
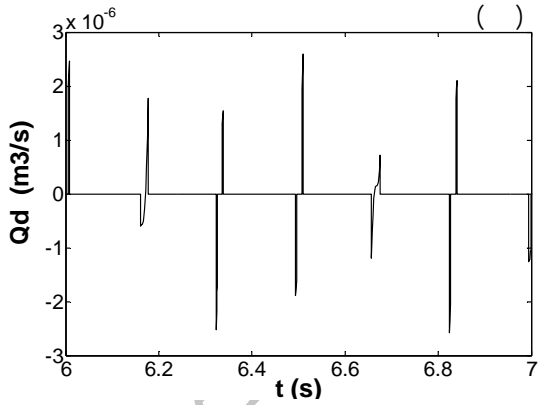
Archive



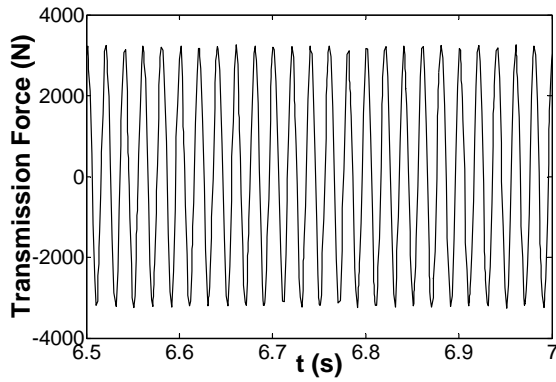
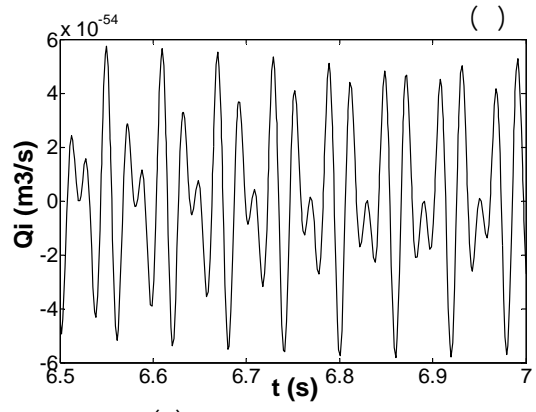
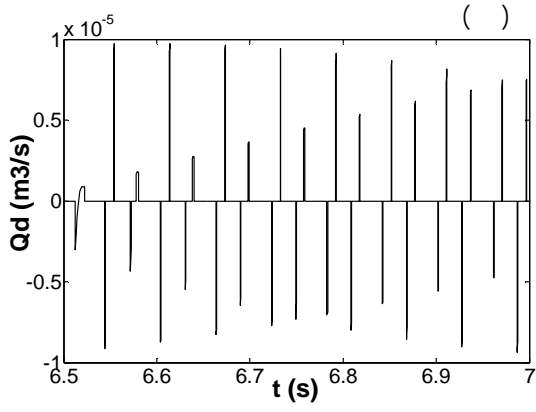




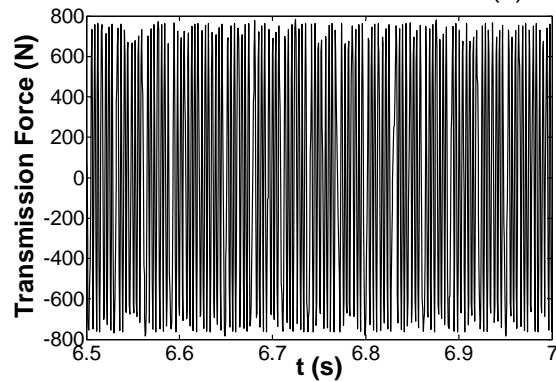
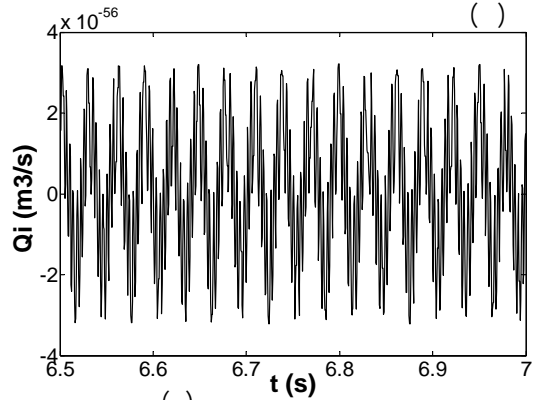
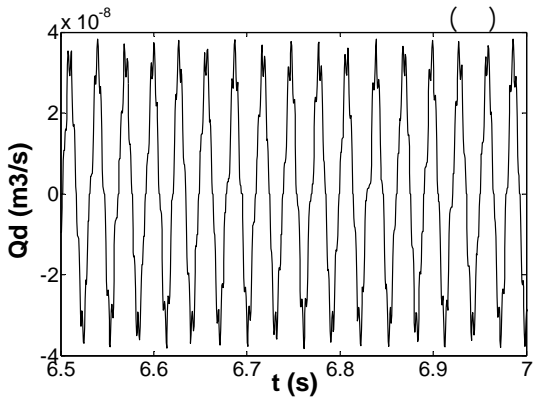
( : 50 Hz 0.1 mm



( : 6 Hz 2 mm

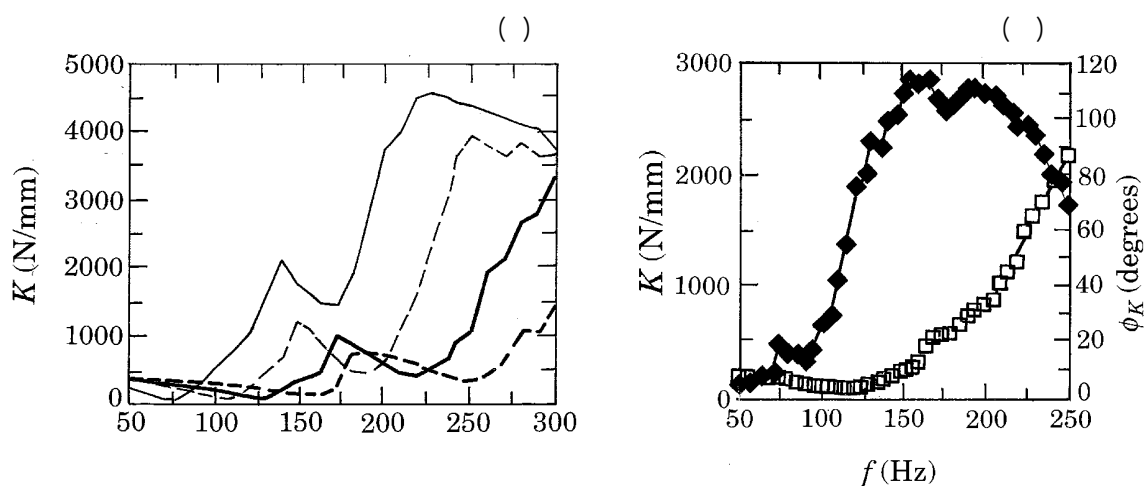


( : 50 Hz 2 mm

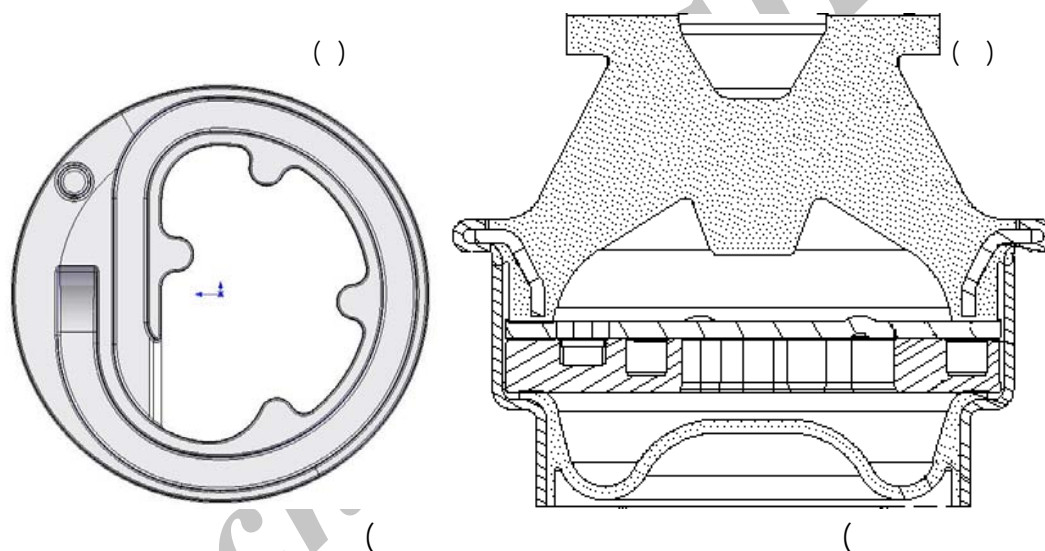


( : 250 Hz 0.1 mm

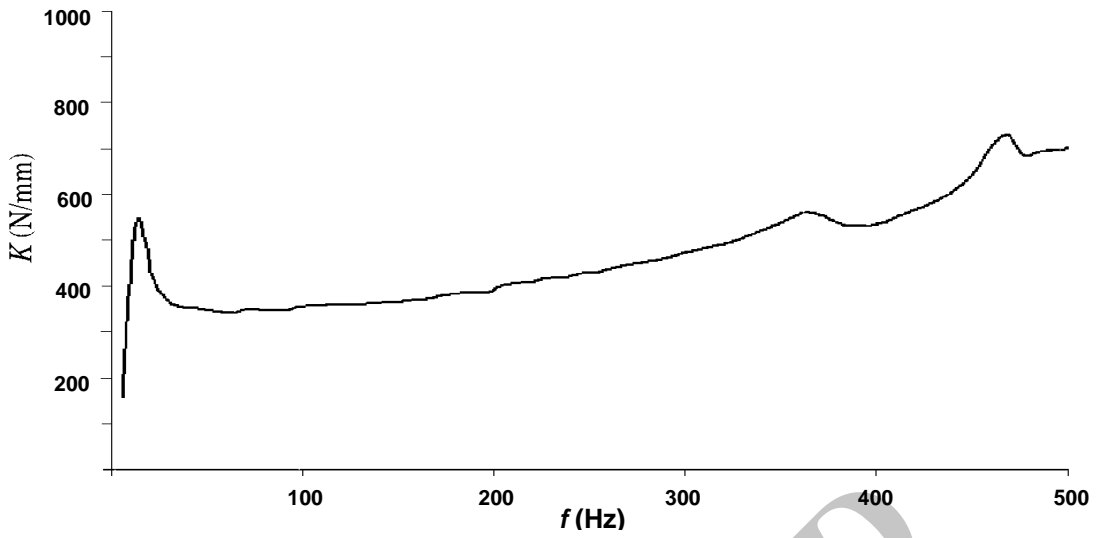
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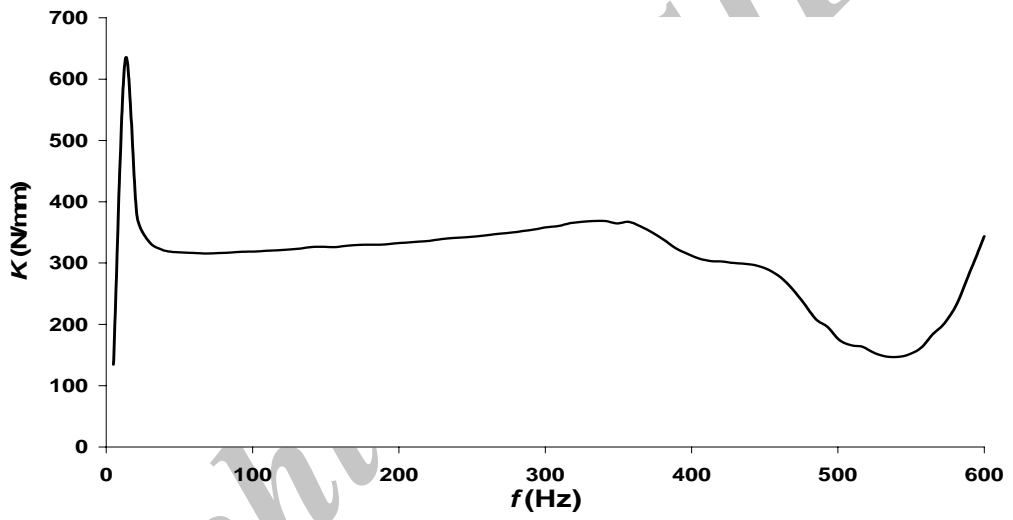
—  $d_0 = 20$  mm , - - - -  $d_0 = 30$  mm , —  $d_0 = 40$  mm , - - - -  $d_0 = 50$  mm



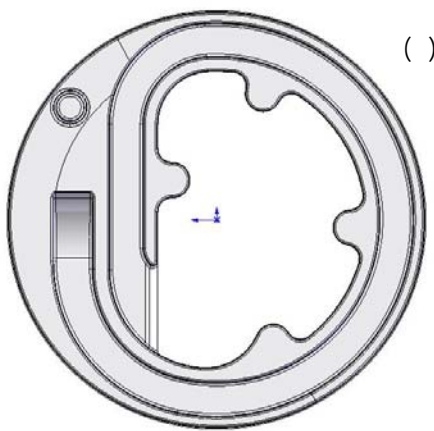
MTS 831.5



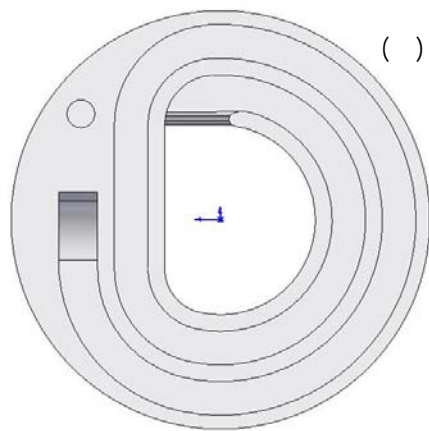
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## Abstract

This paper focuses on the development of a complete non-linear model of a hydraulic engine mount. The model is capable of capturing both the low- and high-frequency behavior of hydraulic mounts. The results presented here provide a significant improvement over existing models by considering all non-linear aspects of a hydraulic engine mount. Current laboratory findings have been used to evaluate nonlinear parameters and hyper-elastic modeling in ANSYS has been used to find complex stiffness. Also switching mechanism of decoupler has been applied. The comprehensive transfer function of linear system has been obtained, by a simultaneous defining of state parameters, scalar output variable and state space matrices. Results indicate two zones of unsatisfactory in system behavior which correspond to the real system performance and experimental data.

The measured responses of the mounts to loading at various frequencies and amplitudes are compared to the predictions of the mathematical model. The comparisons generally show a very good agreement, which corroborate the non-linear model of the mount. It is felt that this work will help engineers in reducing mount design time, by providing insight into the effects of various parameters within the mount.

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