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The Engine Silicone-oil Damper Matching Calculation Method Based on the Heat Balance

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Abstract: By analyzing the internal relations with the silicone-oil damper conditions, the temperature, the viscosity of silicone-oil and the dynamic equilibrium established in the study process. The silicone-oil damper matching calculation method is proposed based on the heat balance established, to prove the validity of the calculation method for the accurately matching calculation and designing method.

Keywords: Heat balance, matching calculation, silicone-oil damper, torsional vibration

INTRODUCTION

The silicone-oil dampers are very simple and efficient, relative to the other kinds of the devices. The main structure of the silicone-oil damper is shown in Fig. 1, the case and the inertia ring are two basic components and the shell of the damper is connected with the crankshaft end, the gap between the housing and the inertia ring is filled with a large viscosity of the silicone-oil, When bearing the high shear, Producing the frictional resistance moment have effect on the engine crankshaft working.

The matching calculation for the damper is also a lack of reliable design calculations, now the silicone-oil damper designing also mostly done in the previous calculation of the theoretical and the empirical formulas (Wen, 1975; Ker, 1971). Accordance with the original designing method to match the damper, it is often not achieving the desired damping effect. Recently with the volume of the diesel engine reduced and the power increases, the development of the modern engines requires the high stable and reliable shock absorber. Therefore the matching calculation method of the silicone-oil damper has important on the intensive study of the engineering application. Mu *et al*. (2004) study the matching calculation about the silicone-oil damper. Wu (2009) have a research of the designing and the test device about the silicone-oil damper in the Desel Egine. Jia *et al*. (2008) have a research of the design and experimental research on fluid viscous dampers. Wolfe *et al*. (2003) study the reduced-order models of nonlinear viscous dampers.

In this study, we show the matching calculation results the viscosity of silicone-oil in the damper, the heat produced, the heat dissipation and the temperature trends. Moreover, we evaluate the performance of the damper, to determine the reasonableness of the parameters matching to study in the resonant region can be in the best damping state. The calculation results (the resonance speed the amplitude and the temperature) have proved the high accuracy of this method in the engineering application.

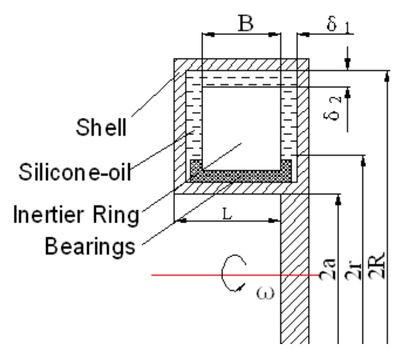

Fig. 1: The structure of the silicone-oil damper

METHODOLOGY

The damper working process of the dynamic heat-balance: When the damper along with the engine running, it's inevitable occurrence of the crankshaft torsional vibration, with the vibration of the damper shell and the high viscosity silicone-oil existing between the shell and the inertia ring due to the shear, will produce the viscous drag torque, reduced the vibration amplitude. The greater the silicone oil suffered the shear stress, the greater to come into being the viscous drag torque. So the effect of the damper in the crankshaft system of the resonance zone is more obvious. At the same time the work done by the viscous torque will be fully converted into heat, the heat dissipation through the shell out-surface

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and also makes the silicone-oil temperature rise, while the silicone-oil viscosity with the increasing temperature will drop and the viscous torque will decline, causing the shaft torsional vibration amplitude increased. When the heat emitted and produced are equal, the temperature of the damper including the silicone oil stabilized. Another the silicone oil suffered the shear and the relative velocity increases, the greater the viscous shear torque is also larger and the relative speed and the shaft vibration amplitude have a close relationship. Because of these properties on the damping factor of the impact of interactions each other and the mutual restraint, the process of making the role of the shock absorber is a very complex dynamic process, will be changed with the engine operating conditions and the environmental factors until a new dynamic equilibrium can be stabilized, particularly in the establishment of a new heat balance, the damper shell surface temperature is be stable.

The calculation models: Before the matching calculation about the damper, the engine crankshaft system will generally simplified, equivalent as a single shaft torsion model, which having the same natural frequency and the vibration energy. With this principle, a simplified model of the crankshaft system with the silicone-oil damper is shown in Fig. 2. J_d is the inertia moment of the inertia ring, C_d is the damping coefficient of the shock absorber, M_e is the engine torque is equivalent to excitation amplitude, J_e the equivalent inertia moment of the crankshaft system, k_e is the equivalent torsional stiffness of the crank shaft system, ω is the excitation frequency (Chen, 1987):

$$\begin{cases} J_d\ddot{\varphi}_d + c_d + \left(\dot{\varphi}_d - \dot{\varphi}_e\right) = 0 \\ J_e\ddot{\varphi}_e - c_d\left(\dot{\varphi}_d - \dot{\varphi}_e\right) + k_e\varphi_e = M_e e^{j\omega t} \end{cases}$$

Can be obtained ΔA the amplitude difference between the inertia ring and the shell of the silicone-oil damper and the shell absolute amplitude A_e:

$$\begin{cases} \Delta A = \dfrac{M_e\omega^2 d_d}{\sqrt{x^2+y^2}} \\ A_e = \dfrac{M_e\sqrt{\left(-\omega^2 d_d\right)^2 + \omega^2 c_d^2}}{\sqrt{x^2+y^2}} \end{cases} \text{And}$$

$$x = J_e J_d\omega^4 - J_e k_d\omega^2 y = \omega c_d\left[k_e - \omega^2\left(J_e + J_d\right)\right] \quad (1)$$

The calculation of dynamic heat-balance:

The viscosity-temperature properties of siliconeoil: The silicone-oil kinematic viscosity drop quickly with the temperature decreased. Through measured by the viscometer, the kinematic viscosity values of 600,000 Cst silicone-oil at the different temperatures are shown in Table 1.

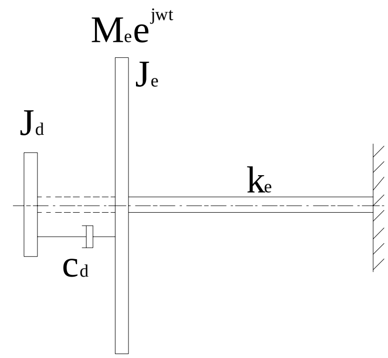


Fig. 2: Simplified model of the engine shaft system with the damper

Table 1: At different temperatures the kinematical viscosity of silicone-oil

t (min)	v (m^2/s)	t (min)	(v m^2/s)
25	0.5691	100	0.1826
50	0.3742	110	0.1606
80	0.2375	120	0.1448

Used with the fitting three least-squares curve method is to get the relationship curve about the silicone-oil kinematic viscosity and the temperature:

$$v = -2.59 \times 10^{-7}\, t^3 + 9.75 \times 10^{-5}\, t^2 - 0.0139t + 0.861$$

The relationship between the silicone-oil viscosity and the shear rate: The viscous damping is essentially generated by the silicone-oil viscosity, the kinematic viscosity affected by the relative velocity and the damper's size, obtained by the empirical formula (Chen, 1987):

$$v' = v\left(\frac{10}{V/\delta}\right)^n = v\left(\frac{10\delta}{\omega.r,\Delta A}\right)^n = v\left(\frac{10\delta}{\omega.\Delta A}\right)^n \frac{1}{r^r}$$

(when the shear rate: $V/\delta < 700$, n = 0.158;
$700 < V/\delta < 1000$, n = 0.424) (2)

Calculated the damping coefficient: from the Newton's law can be obtained by the internal friction drag torque and the radial lateral resistance moment of the damper:

$$M_t = F_t.r = 2\int_r^R 2\pi dr.\, v\left(\frac{10\delta}{\omega.\Delta A}\right)^n \frac{\rho}{r^n}\frac{\omega r\Delta A}{\delta_1}dr$$
$$= \frac{4\times 10^n\pi v\rho}{4-n}\left(\frac{\omega\Delta A}{\delta_1}\right)^{1-n}\left(R^{4-n} - r^{4-n}\right) \quad (3)$$

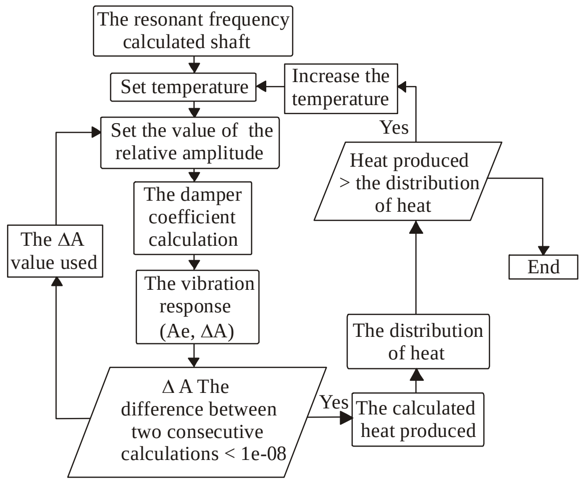


Fig. 3: The heat balance calculation process of the damper

$$M_n = F_n.r = 2\pi RB\nu\left(\frac{10\delta_2}{\omega.\Delta A}\right)^n \frac{\rho}{R^n}\frac{\omega R\Delta A}{\delta_2}.R$$
$$= 2\times 10^n \pi\nu\rho B\left(\frac{\omega.\Delta A}{\delta_2}\right)^{1-n}.R^{3-n} \qquad (4)$$

where ρ is the density of silicone-oil B, δ_1, δ_2, R, r f or the silicone-oil damper dimensions. The damping torque of the lateral resistance torque and the radial moments of the resistance, therefore:

$$M = M_n + M_t = cd\ .\omega.\ \Delta\ A \qquad (5)$$

The Eq. (3) and (4) into (5), obtained the damping coefficient:

$$c_d = \nu\times 2\times 10^n \pi.\rho.(\omega.\Delta A)^{-n}$$
$$\left[\frac{2}{4-n} + \delta_1^{n-1}\left(R^{4-n} - r^{4-n}\right) + B\delta_2^{n-1}.R^{3-n}\right] \qquad (6)$$

RESULT AND DISCUSSION

Analysis of the heat balance calculations:

The calculation of heat produced by thedamper: According to the energy conservation, the damping torque of the power consumed by the heat generated in the system, the shock absorbers per unit time in one cycle of the consumption power for the vibration:

$$Q_s = \pi c_d\,\omega(\Delta A)^2\frac{\omega}{2\pi} = \frac{c_d(\omega\Delta A)^2}{2} \qquad (7)$$

The calculation of heat abstraction by the damper: For the rotating cylinder surface, the heat transfer coefficient with the empirical formula can be expressed as the formula (Ding, 1992):

$\alpha_R = 7.8\times(0.75\omega r)^{0.75} = 6.29\ (\omega.\ r)^{0.75}$ then the calculation of heat release: $Q = \alpha_R A\delta t$.

At this point the outer surface of the silicone-oil damper simplified as a cylinder, the two-side and the inner cylindrical surfaces, the heat abstraction are calculated by:

$Q_1 = 12.58\ \pi\ B.\ \omega^{0.75}\ .R^{1.75}.\ \Delta t$; $Q_2 = 4.57\ \pi\ \omega^{0.75}\ .R^{2.75}.\ \Delta t$; $Q_3 = 12.58\ \pi\ L\ .\ \omega^{0.75}\ .\ a^{1.75}\ .\ \Delta t$

and $\Delta t = t - t_0$, t is the temperature of silicone-oil damper, the ambient temperature is $t0$:

So the total heat release is:

$$Q_f = Q_1 = 2\ Q_2 + Q_3 \qquad (8)$$

The heat-balance calculation method estab-lished: If the surface temperature of the silicone-oil damper can remains stable, that is, to determine by the heat generated and the heat dissipation (the convection and the radiation) from the damper surface.

The question of the heat balance:

$$Q_f = Q_s$$

Still using the simplified single pendulum model, the diesel engine shafting equivalent system parameters, the operating conditions and the sub-harmonic excitation torque as well as the outside ambient temperature is known.

The iterative method for the calculation (Fig. 3): According to the equivalent parameters are known to calculate the natural frequency of the shaft system. First the ambient temperature value as the initial value and then

Table 2: The parameters of the engine crankshaft equivalent system

Description	Mass moment ($kg.m^2$)	Torsinal stiffness (M.Nm/rad)
Free end	0.1742	4.083
Cly.10.1236	3.184	
Cly.20.0875	3.184	
Cly.30.1255	3.223	
Cly.40.1255	3.184	
Cly.50.0875	3.184	
Cly.60.1214	5.381	
Flywheel	3.1532	------

Table 3: The parameters of the silicone-oil damper

Outlet diameter of the inertia ring R_0 (mm)	302.700
Outlet diameter of the inertia ring R_1 (mm)	191.000
Thickness L (mm)	25.300
Gap between the case and the ring δ (mm)	0.500
Inertia of the damper shell J_e ($kg.m^2$)	0.570
Inertia of the inertia ring J_d ($kg.m^2$)	0.123
Mean viscosity silicon-oil (m^2/s)	0.600

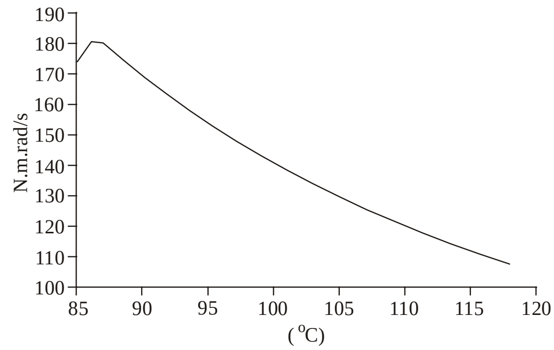
assume that the amplitude of the free end of the shaft, it is desirable minimum (or desirable to a larger value), then by the formula (6) to calculate the silicone damping coefficient, the forced vibrations calculation at the resonance point by the formula (1), get the amplitude of the shell and then return to re-calculate the torque, until the results of the two calculation results is very close. At the end of this iterative process, to get the damper heat value, while the heat produced is lower than the dissipation value, then increased the temperature value, repeat the above calculations until the value of the heat produced and emitted is very close. According to the heat balance the temperature calculated is determined by the damper in the engine load and speed, the calculated torsional vibration amplitude is at the free end point of the engine crankshaft system corresponding to the main harmonic torsional vibration response.

Example calculation: The four-stroke inline 6-cylinder diesel engine with a silicone-oil damper for this study, the diameter of the cylinder bore (mm) 123, the piston stroke (mm) 155, the rated power (kW) 309, the rated speed (rpm) 1900, the lowest/maximum stable speed (rpm) 800-2200. Table 2 gives the parameters of the engine crankshaft equivalent system. Table 3 shows the parameters of the silicone-oil damper.

First the multi-mass moment in the crankshaft system is simplified as a single mass system to calculate. Then $J_e = 0.5632$ $kg.m^2$; $k_e = 7.35e+05$ Nm/rad; 6^{th} order as the main harmonic torsinal vibration to the calculation, the equivalent excitation torque Me = 210.45 Nm.

According to the Fig. 3 on a dynamic heat-balance process calculated by the Matlab program, The harmonic resonance 6^{th} order speed 1760 r/min (torsinal resonate point) in the diesel engine for the heat-balance calculations, the result drawings on the calculation results are as follows:

The results show the temperature rise with the damping it gradually decreased (Fig. 4), because with the increasing temperature, the viscosity of silicone-oil decrease quickly, so the damping coefficient das not decreased rapidly until at the thermal equilibrium



point;Fig. 4: The damping coefficient-temperature curve

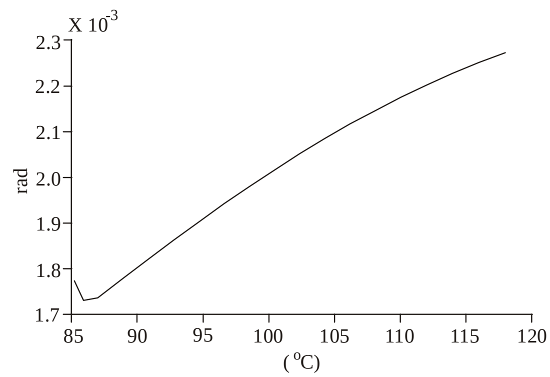


Fig. 5: The relative amplitude-temperature of the shell and the inertia block

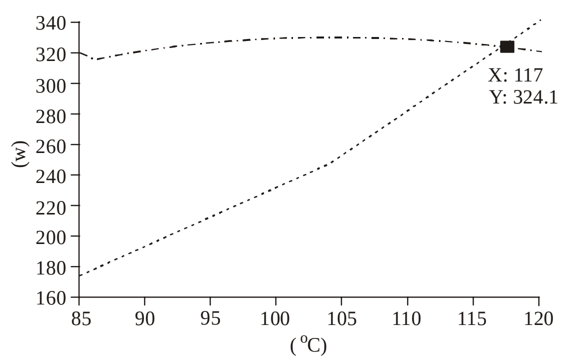


Fig. 6: The damper heat dissipation-produced curve

points; the relative amplitude between the shell and the inertia ring of the damper (Fig. 5); Due to decreased and the viscous damping coefficient decrease with the temperature of the shell rising; The heat produced and emitted, the thermal equilibrium temperature is 117ºC, corresponding to the heat capacity 324.1 watts (Fig. 6), with a trifle of the damper temperature, but the emitted heat rising rapidly until it reaches the thermal equilibrium temperature point, while the torsional amplitude and the of the temperature of the damper are both be in the steady condition. In this condition (Temperature: 117, Speed 1760 r/min) Can calculate out the last torsional amplitude of the damper shell is 0.167 which is the maxim value of the engine shaft system torsional vibration.

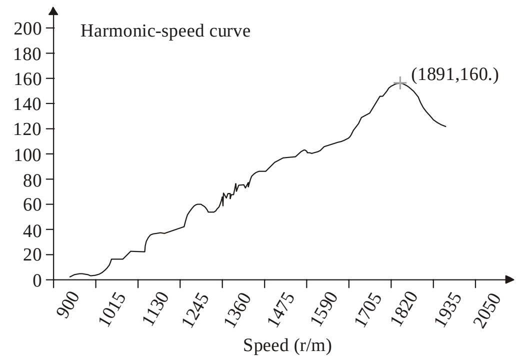


Fig. 7: The test data of the diesel engine torsional vibration

Testing and analysis: In order to verify the accuracy of the matching calculation the damper was installed at the crankshaft free end of this kind of diesel engine, which is on the test bench for the crankshaft torsional vibration test to obtain the main harmonic torsional vibration amplitude and the working damper surface temperature.

The crankshaft speed sensor was mounted on the front of the crankshaft free end. When the engine torsional vibration testing at full load condition, the speed gradually was added from the lowest speed to the maximum speed, automatically sampling the signal by the test software for the data processing and output the test results (Wu, 2009). Through the surface temperature of the silicone-oil damper is tested. Through the test data (Fig. 7) the shaft system 6^{th} order torsional vibration amplitude is 0.16º the measured maximum temperature of the working silicone-oil damper is 120ºC.

Above the calculated values with the measured values is very close, showing that the above calculation method is also more accurate.

CONCLUSION

Based on the damper dynamic heat equilibrium calculations, the matching calculation results not only can well show the viscosity of silicone-oil in the damper, the heat produced, the heat dissipation and the temperature trends, but also to evaluate the performance of the damper, to determine the reasonableness of the parameters matching to work in the resonant region can be in the best damping state.

The calculation results (the resonance speed the amplitude and the temperature) have proved the high accuracy of this method in the engineering application. Through the simulation of the damper working process, to analysis the damping coefficient varies with other parameters, we can make the further understanding about the mechanism of the silicone-oil damper working.

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