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Reduction of Periodic Torsional Vibration using Centrifugal Pendulum Vibration Absorbers

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New developments of more environmentally friendly combustion engines cause high fluctuating torques acting on the crankshaft, drive train and auxiliary units. Those result in noise and vibration that are unintentional, especially in automotive engineering. Dual flywheels to damp the vibration are reaching their limits and alternatives have to be found. Centrifugal pendulum vibration absorbers (CPVA) are a long known, energy saving tool to compensate non-uniform torques. Their main advantage is that they are tuned to a specific order instead of one fixed frequency and therefore they are rotational speed adaptive. This paper presents the fundamentals of CPVA, as well as the equation of motion (EOM), and it shows an analysis for all relevant design parameters.

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1 Introduction

Centrifugal Pendulum Vibration Absorber (CPVA) are a long known device to reduce torsional vibration in rotating systems. They are used successfully in aircraft since the late thirties [1]. To implement these devices into combustion engines of passenger cars, the design space and weight to effectiveness ratio have to be optimized. There are different principal designs of CPVA patented by Kutzbach, Carter, Salomon and Sarazin. In this work the principle by Sarazin is analyzed because of its compact configuration. It consists of one or more pendulums, which act as the absorber mass, that are connected bifilar with the rotor using rollers (Fig. 1). The rollers are free to move in appropriately shaped cutouts relative to the rotor and the pendulums. In the linearized case the absorber frequency f_{abs} can be calculated as a function of the rotational speed of the rotor Ω_{rotor} according to $f_{\text{abs}} = n\Omega_{\text{rotor}}$, where $n = \sqrt{\frac{r}{\rho_0}}$ is a geometric parameter called the tuning order, see Fig. 2. Hence, CPVA can only be tuned to a certain order of excitation instead of one fixed frequency. The order tuning of CPVA is caused by the stiffness of the system, which is related to the centrifugal field.

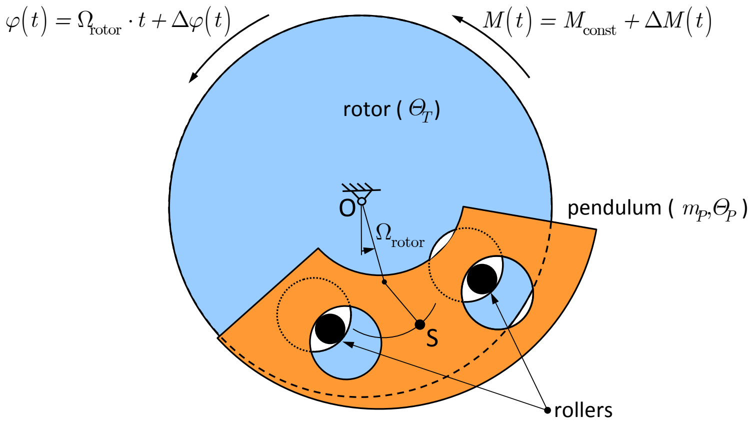

Fig. 1 Design of a CPVA by Sarazin.

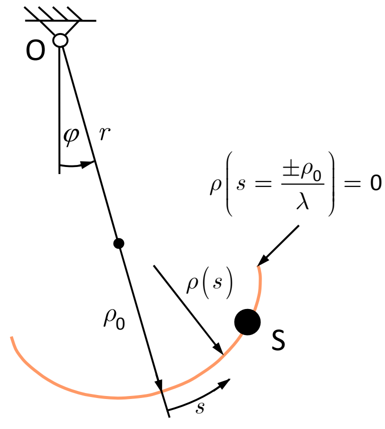

Fig. 2 Geometric scheme.

The rotor is driven by a moment $M(t) = M_{\text{const}} + \Delta M(t)$ consisting of a constant torque M_{const} and a fluctuating torque $\Delta M(t)$ usually of certain order. Assuming viscose damping of the rotor these lead to a rotational speed $\dot{\varphi}(t) = \Omega_{\text{rotor}} + \Delta\dot{\varphi}(t)$ with a constant rotational speed Ω_{rotor} and an overlayed oscillation of the rotor $\Delta\dot{\varphi}(t)$. In the case of equal excitation and tuning order the kinetic energy of the rotor oscillation is stored in potential and kinetic energy of the pendulum leading to a reduced oscillation amplitude of the rotor. For the nonlinear behavior of the CPVA the path on that the pendulum center of mass S moves is important. Madden [2] has shown that a circular path leads to increased rotor amplitudes for larger pendulum amplitudes. This is caused by the changing eigenfrequency of the system with varying pendulum amplitudes. To counteract this effect the tautochronic problem, i.e., the design of a CPVA with an eigenfrequency being independent of the pendulums amplitude, needs to be solved. This leads for a pendulum in a centrifugal field to an epicycloid path.

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2 Equation of Motion

The EOM for a CPVA with epicycloidal pendulum path is derived by Denman [3]. Neglecting the roller masses and damping, assuming only one pendulum, and using the Lagrange equation of second kind results in

$$\begin{bmatrix} \Theta_T + \Theta_P + m_P\left(c^2 - n^2 s^2\right) & m_P\chi \\ m_P\chi & m_P \end{bmatrix} \begin{pmatrix} \ddot{\varphi} \\ \ddot{s} \end{pmatrix} + \begin{pmatrix} 2\dot{\varphi}\dot{s} m_P n^2 s + \dot{s}^2\left(-m_P n^2(1+n^2)\frac{s}{\chi}\right) \\ \dot{\varphi}^2 m_P n^2 s \end{pmatrix} = \begin{pmatrix} M(t) \\ 0 \end{pmatrix} \quad (1)$$

$$\text{with} \qquad \chi = \sqrt{c^2 - n^2(1+n^2)s^2} \qquad \text{and} \qquad c = \rho_0 + r. \quad (2)$$

3 CPVA parameters

There are mainly four parameters that influence the performance of CPVA. Assuming a CPVA with epicycloidal pendulum path, the main issue is to avoid the pendulum reaching the ends of the path where the radius of curvature $\rho(s)$ equals zero (see Fig. 2), while still having a small, lightweight design that can handle large fluctuating torques. Hitting the end of the epicycloidal path would cause higher order excitations of the system and could possibly damage the pendulum support. Increased pendulum mass m_P or increased center of mass distance c allows larger fluctuating input torque $\Delta M(t)$ for the same pendulum amplitudes. Hereby the mass m_P has a linear influence while the influence of the center of mass distance c is quadratic. Another parameter is the rotational speed of the rotor Ω_{rotor} which has also a quadratic influence on the possible applied torque amplitudes. With higher rotational speed of the rotor the stiffness of the system increases, hence higher fluctuating torques can be applied.

For a limited design space detuning can be used as well to stop the pendulum from reaching the ends of the epicycloidal path. The principle of detuning is shown in Fig. 3. Thereby the tuning order is chosen to be a little higher than the excitation order leading to smaller pendulum amplitudes (upper figure) but larger rotor oscillation (lower figure). The effectiveness of the CPVA, which is defined as the rotor amplitudes with free pendulums $\hat{\varphi}_{\text{free}}$ divided by the rotor amplitudes with fixed pendulums $\hat{\varphi}_{\text{fix}}$, depends on the detuning, damping of the pendulum, and the pendulum amplitude itself. With increasing pendulum amplitudes the effectiveness can decrease by 20 to 40 percent depending on the tuning order n, see Fig. 4. The reason for this can be found in the higher radial component of the pendulum movement for larger pendulum amplitudes, hence the mass forces of the pendulum are not acting fully tangential to the rotor.

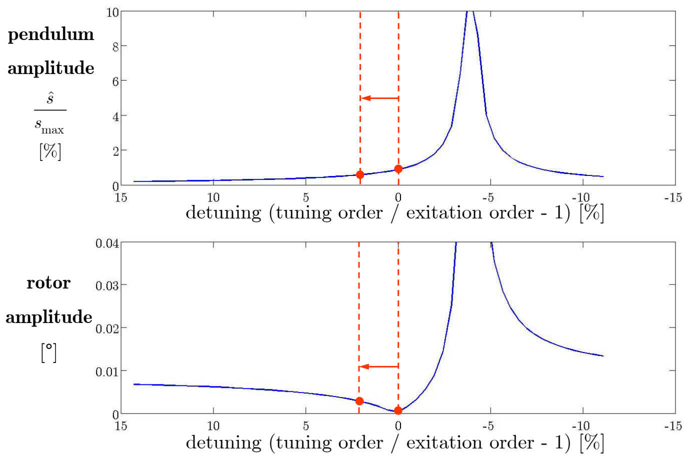

Fig. 3 The principle of detuning explained at the amplitude frequency diagram

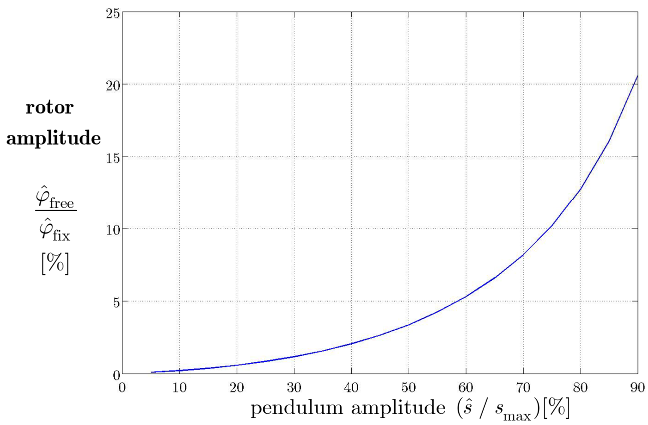

Fig. 4 Influence of the pendulum amplitude on effectiveness

4 Conclusion

The use of CPVA is a very effective option to reduce torsional vibration of certain order as demonstrated in early applications in aircraft. To use CPVA in modern combustion engines the design has to be optimized to minimize space and weight. CPVA can be implemented at the crankshaft, flywheel, or counterbalance shaft with the advantage to use existing masses as absorber mass. To use CPVA over the complete range of input torque the pendulum center of mass has to move on an epicycloidal path. CPVA can not vanish the torsional vibration but can reduce them significantly.

References

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