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Dynamics of synchronization of rotational motion of contacting triple-body systems

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ABSTRACT

Dynamics of synchronization of rotational motion of contacting triple-body system is studied. It is assumed that all bodies of the system can rotate completely independently of one another and perform rotational motion about the same axis under the action of external and internal loads. The direct dynamics synchronization problem for the contacting triple-body system is stated and the algorithm of the solution of the problem is presented. To determine the synchronization time the transcendental equation is derived. The torques between contacting interfaces are determined by solving two integral equations. Finally, by knowing synchronization time and the torques between contacting interfaces, the rotational motion of the system during synchronization process is determined by integration of the governing equations with prescribed initial conditions. It was shown that the solution of the direct dynamics problem is not unique and the synchronizing torques can be subject to optimization. The obtained results are applied for a generic synchronizer mechanism of manual transmission systems. Assuming that the drag torque, the vehicle resistance torque, the control torque applied to the selector sleeve, and the synchronizing torques at the contacting interfaces are substantially constant during synchronization the solution of the direct dynamics synchronization problem for a generic synchronizer is obtained in analytical form. Sensitivity analysis of the synchronization time and the gear shifting comfort with respect to the control torque applied to the selector sleeve and the driveline vibration has presented.

Keywords: Synchronizer mechanism, Transmission system, Synchronization time, Gear shifting comfort, Driveline vibration.

1 INTRODUCTION

Different engineering systems often comprise power transmission with gearbox. To perform gear shifting synchronizer mechanisms have been developed. Transmission gear shifting improvement with respect to smooth, quick and energy efficient synchronizer's performance, is still one of the major concern area for automotive industry, see e.g. [1-6]. Typical synchronization process includes different phases of relative motion between functional components of synchronizer and gearbox that should be described by taking into account contact phenomenon in contacting interfaces, lubrication, temperature, and other issues, see e.g. [4-13]. So, the dynamics of synchronization processes is a challenge. Solution to this engineering problem requires deep insight into the dynamics and optimization of multibody system used to model the synchronization processes in power transmissions.

Aiming modelling and analysis of dynamics of synchronizing processes in vehicle transmission systems the paper is focused on main synchronization phase, namely the case when all bodies of the synchronizer mechanism are in contact. As an engineering model of a generic synchronizer the contacting triple-body system is proposed. It is assumed that all bodies of the system can rotate completely independently of one another and perform rotational motion about the same axis under the action of external and internal loads. The direct dynamics synchronization problem for the contacting triple-body system (CTBS) is considered. For given external loads it is required to determine the torques between contacting interfaces and the rotational motion of the system that all together satisfy the equations of motion, prescribed initial conditions and guarantee synchronization of rotational speeds of all bodies for the final time.

2 MODEL AND PROBLEM STATEMENT

Consider the multibody system depicted in Figure 1. The system consists of three rigid bodies: B1, B2, and B3. It is assumed that all bodies of the CTBS can rotate completely independent of one another and perform rotational motion about the same axis Ox under the action of external and internal loads. The external load comprises the prescribed torque $M_v(t)$ and the control torque $M_F(t)$ both acting on the body B1, and the prescribed torque $M_d(t)$ acting on the body B3. The internal load comprises the synchronizing torque $M_s(t)$ acting at the contacting interface between the body B1 and the body B2, and the synchronizing torque $M_r(t)$ acting at the contacting interface between the body B2 and the body B3.

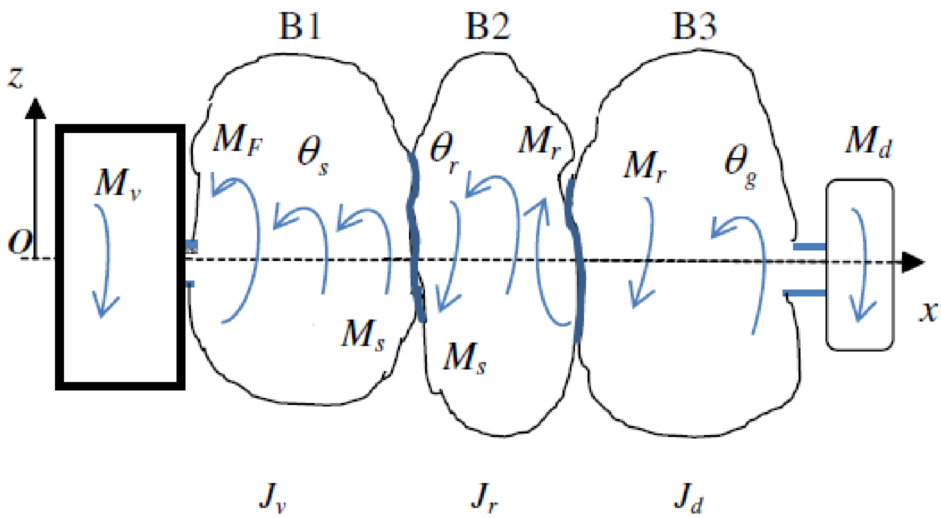

Figure 1. Sketch of the contacting triple-body system

With above mentioned assumptions the considered CTBS has three degrees of freedom. Using free body diagram the equations of rotational motion of the system in question can be written as follows (see Figure 1):

$$J_v\ddot{\theta}_s(t) = M_s(t) - M_v(t) + M_F(t) \tag{1}$$

$$J_r\ddot{\theta}_r(t) = M_r(t) - M_s(t) \tag{2}$$

$$J_d\ddot{\theta}_g(t) = -M_d(t) - M_r(t) \tag{3}$$

Here $\theta_s, \theta_r, \theta_g$ are the angular coordinates of the bodies B1, B2 and B3, respectively. J_v, J_r, J_d are the moments of inertia of the bodies B1, B2 and B3, respectively.

Let assume that at the initial time instant, $t = 0$, the phase state of the CTBS is prescribed by the following conditions:

$$\theta_s(0) = \theta_{s0}, \quad \dot{\theta}_s(0) = \omega \tag{4}$$

$$\theta_r(0) = \theta_{r0}, \quad \dot{\theta}_r(0) = r_1\omega \tag{5}$$

$$\theta_g(0) = \theta_{g0}, \quad \dot{\theta}_g(0) = r\omega \tag{6}$$

Here in the expressions (4) - (6), $\theta_{s0}, \theta_{r0}, \theta_{g0}, \omega, r_1, r$ are given numbers, and $r_1 > 0, r > r_1, r > 1$.

The following direct dynamics synchronization problem (DDSP) can be stated.

Problem DDSP: Let we are given by the external prescribed torque $M_v(t)$ acting on the body B1

$$M_v = M_{vg}(t), \quad t \geq 0 \tag{7}$$

the external prescribed torque $M_d(t)$ acting on the body B3

$$M_d = M_{dg}(t), \quad t \geq 0 \tag{8}$$

the control torque applied to the body B1

$$M_F = M_{Fg}(t), \quad t \geq 0 \tag{9}$$

and the initial conditions (4)-(6).

It is required to determine synchronizing torques between the contacting interfaces, $M_r(t), M_s(t)$, the rotational motion of the CTBS, $\theta_s(t), \theta_r(t), \theta_g(t)$, and the time instant, $t = t_s$, that all together satisfy the equations (1)-(3), the initial conditions (4)-(6), and the following final conditions

$$\dot{\theta}_s(t_s) = \dot{\theta}_r(t_s) = \dot{\theta}_g(t_s) = r\omega \tag{10}$$

Note that the angular coordinates at the final time instant $t = t_s$, i.e. the values $\theta_s(t_s), \theta_r(t_s), \theta_g(t_s)$ are free. The parameter t_s will be termed the synchronization time.

3 ALGORITHM OF THE SOLUTION OF THE DDSP

Assuming that the torques M_v, M_d, M_F, M_s, M_r are the functions of time the following notations can be introduced:

$$
\begin{aligned}
&M_{s1}(t)=\int_0^t M_s(\tau)d\tau, \quad M_{s2}(t)=\int_0^t M_{s1}(\tau)d\tau \\
&M_{r1}(t)=\int_0^t M_r(\tau)d\tau, \quad M_{r2}(t)=\int_0^t M_{r1}(\tau)d\tau \\
&M_{v1}(t)=\int_0^t M_{vg}(\tau)d\tau, \quad M_{v2}(t)=\int_0^t M_{v1}(\tau)d\tau \\
&M_{d1}(t)=\int_0^t M_{dg}(\tau)d\tau, \quad M_{d2}(t)=\int_0^t M_{d1}(\tau)d\tau \\
&M_{F1}(t)=\int_0^t M_{Fg}(\tau)d\tau, \quad M_{F2}(t)=\int_0^t M_{F1}(\tau)d\tau
\end{aligned} \tag{11}
$$

By integrating the equations (1)-(3) with initial conditions (4)-(6) and using the notations (11), the angular velocities and angular coordinates of the rotating bodies of the CTBS are expressed as follows:

$$
\begin{aligned}
&\dot{\theta}_s(t)=[M_{s1}(t)-M_{v1}(t)+M_{F1}(t)]/J_v+\omega \\
&\dot{\theta}_r(t)=[M_{r1}(t)-M_{s1}(t)]/J_r+r_1\omega \\
&\dot{\theta}_g(t)=[-M_{d1}(t)-M_{r1}(t)]/J_d+r\omega
\end{aligned} \tag{12}
$$

$$
\begin{aligned}
&\theta_s(t)=[M_{s2}(t)-M_{v2}(t)+M_{F2}(t)]/J_v+\omega t+\theta_{s0} \\
&\theta_r(t)=[M_{r2}(t)-M_{s2}(t)]/J_r+r_1\omega t+\theta_{r0} \\
&\theta_g(t)=[-M_{d2}(t)-M_{r2}(t)]/J_d+r\omega t+\theta_{g0}
\end{aligned} \tag{13}
$$

Using the conditions of synchronization (10), the expressions (12) and the notations (11), the following system of the integral-transcendental equations for unknown synchronization time t_s and synchronizing torques $M_r(t), M_s(t)$ are obtained:

$$
\int_0^{t_s}[M_s(t)-M_{vg}(t)+M_{Fg}(t)]\mathrm{dt}=J_v\omega(r-1) \tag{14}
$$

$$\int_0^{t_s}[M_r(t)-M_s(t)]\mathrm{dt}=J_r\omega(r-r_1) \tag{15}$$

$$\int_0^{t_s}[-M_{dg}(t)-M_r(t)]\mathrm{dt}=0 \tag{16}$$

By summing the equations (14)-(16) we will get

$$\int_0^{t_s}[M_{Fg}(t)-M_{vg}(t)-M_{dg}(t)]\mathrm{dt}=\omega[J_v(r-1)+J_r(r-r_1)] \tag{17}$$

Analysis of the obtained equation (17) shows that for the considered CTBS and the synchronization conditions the synchronization time t_s is determined only by the external loads and the inertial properties of the body B1 and the body B2, and does not depend on the internal synchronizing torques. It means that within the considered assumptions the quickness of the synchronization of the CTBS does not depend on the inertial properties of the body B3 as well as the internal load distributions at the contacting interfaces between the body B1 and the body B2, and between the body B2 and the body B3.

It is also obvious that the external torques, $M_{dg}(t), M_{Fg}(t), M_{vg}(t)$, can't be chosen arbitrary. These torques must be chosen in that way that it is guaranteed the existing at least one positive root of the transcendental equation (17) with respect to parameter t_s. In this case by knowing the synchronization time t_s, the corresponding internal synchronizing torques $M_r(t), M_s(t)$ are determined by solving the equations (15), (16).

As it follows from analysis of the equations (15) and (16) the functions $M_r(t), M_s(t)$ are not determined uniquely. That is, if for the prescribed external loads (7)-(9) the solution to the Problem DDSP exist, then the solution is not unique. Consequently, the solution of the direct dynamics synchronization problem for the considered CTBS can be subject to optimization.

Finally, knowing the synchronization time t_s and the toques at the contacting interfaces $M_r(t), M_s(t)$, the rotational motion of the CTBS that satisfy the boundary conditions (4)-(6), (10) is obtained from expressions (12) and (13). It concludes the algorithm of the solution of the formulated direct dynamics synchronization problem for the CTBS.

4 DYNAMICS OF A GENERIC SYNCHRONIZER

Let assume that the considered CTBS models a generic synchronizer mechanism during the main synchronization phase in the vehicle manual transmission. The bodies B1, B2 and B3 will be termed the selector sleeve, the blocker ring and the gearwheel, respectively. The external load comprises: the torque $M_v(t)$, the vehicle resistance acting on the output side of the gearbox; the control torque $M_F(t)$ acting on the selector sleeve, (the torque arising due to the external axial force applied to selector level); and the torque $M_d(t)$, the drag torque acting on the input side of the gearbox. The internal load comprises the synchronizing torque $M_s(t)$ acting at the contacting interface between the selector sleeve and the blocker ring and the synchronizing torque $M_r(t)$ acting at the contacting interface between the blocker ring and the gearwheel.

Now in (4) - (17) ω is the initial angular velocity of the output side of the synchronizer; *r* is the gear step, i.e. the ratio of the initial angular velocity of the input and the output sides of the synchronizer; J_d, J_v are the equivalent moment of inertia of the input (engine clutch) and output (all vehicle components including that of vehicle itself) sides of the gearbox, respectively; J_r is the moment of inertia of the blocker ring of the synchronizer mechanism.

Following [11, 12] and assuming that the resistance torque on the synchronizer owing to the vehicle inertia, the drag torque and the synchronizing torques at the contacting interfaces are substantially constant during the synchronization process consider the Problem DDSP with the following assumptions:

$$
\begin{aligned}
&M_{vg}(t) = M_{v0} = \text{constant}, \quad M_{dg}(t) = M_{d0} = \text{constant}, \quad t \geq 0 \\
&M_r(t) = M_{r0} = \text{constant}, \quad M_s(t) = M_{s0} = \text{constant}, \quad t \geq 0
\end{aligned} \tag{18}
$$

Let assumed also that the external control torque $M_F(t)$ has a constant value during synchronization, i.e.

$$
M_F(t) = M_{F0} = \text{constant}, \quad t \geq 0 \tag{19}
$$

With assumptions (18) and (19) by using the expressions (13) with notations (11) and the equations (15)-(17), the solution to the direct dynamics synchronization problem for the generic synchronizer is determined as follows:

$$
t_s(M_{F0}) = \frac{\omega[J_v(r-1) + J_r(r-r_1)]}{M_{F0} - M_{v0} - M_{d0}} \tag{20}
$$

$$
\begin{aligned}
&M_{r0} = -M_{d0} \\
&M_{s0} = \frac{J_v(1-r)M_{d0} + J_r(r_1 - r)(M_{F0} - M_{v0})}{J_v(r-1) + J_r(\mathrm{r} - r_1)}
\end{aligned} \tag{21}
$$

$$
\begin{aligned}
&\theta_s(t) = t^2(M_{s0} - M_{v0} + M_{F0})/(2J_v) + \omega t + \theta_{s0} \\
&\theta_r(t) = t^2(M_{r0} - M_{s0})/(2J_r) + r_1\omega t + \theta_{r0} \\
&\theta_g(t) = r\omega t + \theta_{g0}
\end{aligned} \tag{22}
$$

By taking into account that $r > 1, r > r_1$ and the synchronization time must be positive, from (20) follows the restriction on the external control torque applied to the selector sleeve

$$M_{v0}+M_{d0}<M_{F0}\le M_F^{\max} \qquad (23)$$

Here in (23) $M_F^{\max}$ is the maximal admissible value of the external control torque $M_F(t)$.

From the expression (20) it follows that the larger torque M_{F0} applied to the sleeve the smaller synchronization time t_s will be. In case of restriction (23) the minimal value of the synchronization time, $t_s^{\min}$, is determined by the expression

$$t_s^{\min}=\frac{\omega[J_v(r-1)+J_r(r-r_1)]}{M_F^{\max}-M_{v0}-M_{d0}} \qquad (24)$$

4.1 Driveline vibration and synchronization time

Consider the dynamics of a generic synchronizer mechanism for the case when the vehicle resistance acting on the output side of the gearbox, $M_{vg}(t)$, is subject to periodic excitations. Namely, let us assume that the torque $M_{vg}(t)$ is prescribed as follows

$$M_{vg}(t)=M_{v0}+A_v\sin(\omega_v t+\varphi_v) \qquad (25)$$

Here A_v, ω_v, φ_v are the amplitude, the frequency and the phase angle of the periodic excitations applied to the output side of the gearbox (driveline vibrations).

The drag torque, the synchronizing torques at the contacting interfaces as well as the external control torque applied to the selector sleeve are assumed to be substantially constant during the synchronization and satisfy the conditions (18) and (19).

With the above assumptions and the expression (25) the equation (17) can be written as follows

$$\int_0^{t_s}[M_{F0}-M_{v0}-M_{d0}-A_v\sin(\omega_v t+\varphi_v)]\mathrm{dt}=\omega[J_v(r-1)+J_r(r-r_1)] \qquad (26)$$

By introducing the notation

$$t_{s0}=\frac{\omega[J_v(r-1)+J_r(r-r_1)]}{M_{F0}-M_{v0}-M_{d0}} \qquad (27)$$

the equation (26) gives the following relation

$$t_s=t_{s0}+\frac{A_v\left[\cos\varphi_v-\cos(\omega_v t_s+\varphi_v)\right]}{\omega_v(M_{F0}-M_{v0}-M_{d0})} \qquad (28)$$

Here t_s and t_{s0} are the synchronization times with and without driveline vibrations, respectively, (see and compare the expressions (20) and (27)).
Let us assume that we are given by the periodic excitation (25) with zero phase angle, i.e. $\varphi_v = 0$. Then as it follows from the expression (28) we have the relation

$$t_s = t_{s0} + \frac{A_v\left[1-\cos(\omega_v t_s)\right]}{\omega_v (M_{F0} - M_{v0} - M_{d0})} \tag{29}$$

Analysis of the relation (29) shows that for all feasible synchronization processes with the admissible control torque $M_{F0} > M_{v0} + M_{d0}$ the driveline vibration prescribed by the expression $M_{vg}(t) = M_{v0} + A_v \sin\omega_v t$ will increase the synchronization time, i.e. $t_s > t_{s0}$, for any values of the amplitude and the frequency of the periodic excitation.

Consider the periodic excitation (25) with the phase angle $\varphi_v = -\pi/2$, i.e. the case when the driveline vibration is prescribed by the expression

$$M_{vg}(t) = M_{v0} - A_v \cos\omega_v t \tag{30}$$

From the expression (28) we can obtain

$$t_s = t_{s0} - \frac{A_v \sin\omega_v t_s}{\omega_v (M_{F0} - M_{v0} - M_{d0})} \tag{31}$$

Analysis of the relation (31) shows that one can expect that the driveline vibration prescribed by the expression (30) can shorten the synchronization time t_s. For instance, if $\omega_v t_s \ll 1$, then $\sin\omega_v t_s \approx \omega_v t_s$ and the relation (31) gives the following

$$t_s = t_{s0} - \frac{A_v t_s}{M_{F0} - M_{v0} - M_{d0}} \tag{32}$$

i.e. the inequality $t_s < t_{s0}$ is valid for all $A_v > 0$ and $M_{F0} > M_{v0} + M_{d0}$.

4.2 Time-comfort optimal gear shifting

Quick gear shifting can lead to clashing, double bump, and other phenomena in a transmission system which effect negatively gear shifting comfort.

Let us assume that the total inertia load acting on the synchronizer mechanism

$$Q_C(M_{F0}) = J_v\ddot{\theta}_s(M_{F0}) + J_r\ddot{\theta}_r(M_{F0}) + J_d\ddot{\theta}_g(M_{F0}) \tag{33}$$

can be used as an indicator of the gear shifting comfort. Moreover, it is assumed that the lowest value of the function (33) corresponds to the best comfort.

With the expressions (22) the function (33) becomes

$$Q_C(M_{F0}) = M_{F0} - M_{v0} - M_{d0} \tag{34}$$

Analysis of the functions $t_s(M_{F0})$ and $Q_C(M_{F0})$ expressed by (20) and (34), shows that there exist the control torque M^*_{F0} such that the following system of variational equations are obeyed

$$\begin{aligned} &\min_{M_{F0}\in U_F} t_s(M_{F0}) = t_s(M^*_{F0}) \\ &\min_{M_{F0}\in U_F} [Q_C(M_{F0})] = Q_C(M^*_{F0}) \end{aligned} \tag{35}$$

Here in (35) U_F is a set of admissible control torques defined by the inequalities (23).

The variational equations (35) together with the inequalities (23) constitute the time-comfort Pareto optimal control problem for considered generic synchronizer mechanism. The solution to this problem is given by the following expressions [14]:

$$\begin{aligned} &M^*_{F0} = M_{v0} + M_{d0} + \sqrt{M_F^{\max}(M_F^{\max} - M_{v0} - M_{d0})} \\ &t_s(M^*_{F0}) = \frac{\omega[J_v(r-1) + J_r(r-r_1)]}{\sqrt{M_F^{\max}(M_F^{\max} - M_{v0} - M_{d0})}} \\ &Q_C(M^*_{F0}) = \sqrt{M_F^{\max}(M_F^{\max} - M_{v0} - M_{d0})} \end{aligned} \tag{36}$$

5 CONCLUSIONS

In the paper a contacting triple-body system dynamics is studied with focus on synchronization of its rotational motion. The direct dynamics synchronization problem is stated and the algorithm of the solution of the problem has developed. It was found that within the considered assumptions the synchronization time is determined only by the external loads and does not depend on internal synchronizing torques at contacting interfaces. It is also proved that for given external loads the solution of the direct dynamics synchronization problem is not unique and can be subject to optimization.

The obtained results have been applied to study the dynamics of a generic synchronizer mechanism of a vehicle transmission system. The solution of the direct dynamics synchronization problem was obtained in an analytical form. Sensitivity of the synchronization time with respect to driveline periodic excitations was studied. It was found that the values of the phase angle, the amplitude and the frequency of driveline periodic excitations significantly affect the synchronization time. Driveline vibrations can increase or decrease the synchronization time. It was shown that the synchronization time is heavily sensitive with respect to the phase angle of the driveline periodic excitations.

For the considered generic synchronizer mechanism the problem of time-comfort optimal control of gear shifting was stated and its solution has presented.

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