UNIVERSITY OF NIŠ
The scientific journal **FACTA UNIVERSITATIS**
Series: **Mechanical Engineering** Vol.1, N^{o} 5, 1998 pp. 537 - 545
Editor of series: Nenad Radojković, e-mail: radojkovic@ni.ac.yu
Address: Univerzitetski trg 2, 18000 Niš, YU
Tel: +381 18 547-095, Fax: +381 18 547-950
http://ni.ac.yu/Facta

STARTING OF AN ELECTRIC MOTOR DRIVE WITH HYDRODYNAMIC COUPLING

UDC:621.311.13

Dušan Uzelac, Rastislav Šostakov, Slobodan Tašin

Faculty of Technical Sciences, Trg Dositeja Obradovića 6, Novi Sad, Yugoslavia

Abstract. *Starting of an electric motor drive with hydrodynamic coupling is a transient operation regime beginning with the start of a driving electric motor and lasting to its steady-state operation. It is important to explore this process as it can be used as the basis for evaluation of relevant parameters used for the choice of the motor and power transmission elements. This includes the calculation of starting intervals of a driving motor (it has to be short enough) and an output operating device (it has to be long enough), determination of the thermal and mechanical loading of driving mechanism elements, etc. The paper contains, as an example, a proposition for a short and sufficiently exact calculation procedure of a hydrodynamic coupling starting regime.*

Key words: *power transmissions, hydrodynamic couplings, transient operation regime*

LIST OF SYMBOLS:

Basic symbols:

I	[kgm]	– mass moment of inertia
J	[A]	– current
M	[Nm]	– torque
P	[kW]	– power
ΔP	[kW]	– power loss
t	[s]	– time
Δt_z	[s]	– staffing interval
U	[V]	– electric voltage
ω	[s^{-1}]	– angular velocity
$\dot{\omega}$	[s^{-2}]	– angular acceleration
f	[Hz]	– frequency

Subscripts:

1	– shaft 1, coupling entrance
2	– shaft 2, coupling exit
h	– hydraulic
hs	– hydrodynamic coupling
i, j	– current values
m	– motor
max	– maximum value
n	– nominal value
P	– pump impeller
pm	– driving motor
ru	– operating device
T	– turbine impeller
z	– stopping (when $\omega_2 = 0$)

Received July 10, 1998

1. INTRODUCTORY REMARKS

The hydrodynamic couplings are elements of power transmissions that have came into use relatively recently. The first hydrodynamic coupling was used in 1910th in ship driving mechanism. Since then, hydrodynamic couplings are widely used because of their simple construction, easy maintenance, operational confidence, automatic adapting to loading changes, easier starting, ability to transmit large power with small dimensions and protection of driving motor from overloading and dynamic loading. Hydrodynamic couplings are especially used in transport devices for continuous and discontinuous transport, agricultural machines, food processing equipment for food, as well as in tanning and chemical industry, in mining machines, etc.

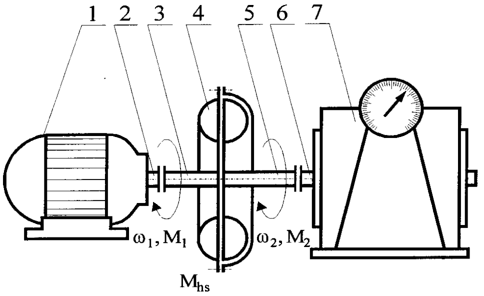
Hydrodynamic couplings enable regular start of a driving mechanism. With adequate choice of hydrodynamic coupling, it is possible to achieve fast passing through unfavorable operating regimes of driving electric motor, but enough long starting period of operating device.

In order to estimate the thermal and mechanical loading of driving mechanism elements, it is necessary to track the changing of the input and output torque, input and output angular velocities and power losses in dependence on the accelerating time.

It will be shown that it is possible to determine the starting regime duration by solving the mathematical model of driving mechanism. However, it is necessary to define the driving system before formulating the mathematical model.

2. DRIVING MECHANISM

The driving mechanism shown in Fig. 1 consists of electric motor, hydrodynamic coupling and a brake simulating the operating device. Electric motor is firmly connected to the pump section of the hydrodynamic coupling, therefore they run at the same angular velocity ω_1. Similarly, operating device is stiffly connected to the turbine section of the hydrodynamic coupling, and they run at the angular velocity ω_2. Input torque of hydrodynamic coupling is M_1 and output torque is M_2. Pump section of hydrodynamic coupling delivers torque M_{hs} to the turbine section.



1. Electric motor
2. Electric motor shaft
3. Input shaft of the hydrodynamic coupling
4. Hydrodynamic coupling
5. Output shaft of the hydrodynamic coupling
6. Operating device shaft
7. Operating device

Fig. 1. Driving mechanism

Steady-state torque characteristic curves of driving motor, hydrodynamic coupling and operating device are known and are shown in Fig. 2, Fig. 3 and Fig. 4.

Torque characteristic of a driving motor (induction motor Fig. 2) is given for constant electric voltage ($U = const$) and frequency ($f = const$) and it shows the torque on the motor shaft when the rotation is stationary. Following characteristic points, i.e. operating regimes, can be noticed on the torque characteristic curve: starting/stopping regime ($M_m = M_{mz}$; $\omega_m = 0$), maximum torque regime ($M_m = M_{max}$) and nominal[1] regime ($M_m = M_{mn}$; $\omega_m = \omega_{mn}$).

Universal torque characteristic of a hydrodynamic coupling (Fig. 3) shows the value of the torque handed over from pump to turbine section in dependence on the angular velocities of pump and turbine sections. It is well known that only in the case of stationary rotation ($\omega_1 = const$; $\omega_2 = \text{const}$) and negligible mechanical losses, it can be assumed with sufficient accuracy that input torque of hydrodynamic coupling M_1 is equal to the output torque M_2.

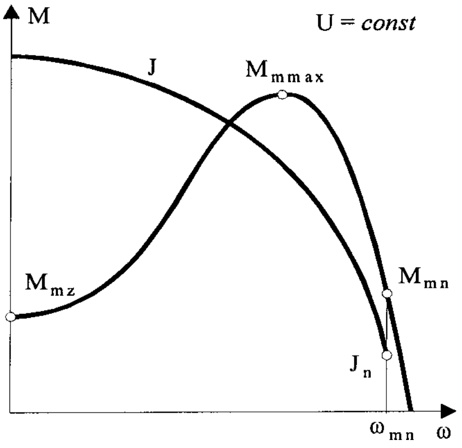


Fig. 2. Torque characteristic of a driving motor (induction motor)

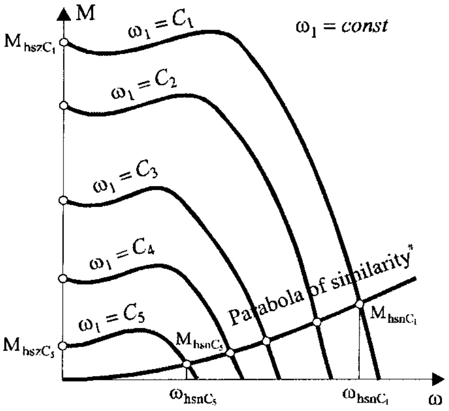


Fig. 3. Torque characteristic of a hydrodynamic coupling

When a hydrodynamic coupling is accelerating (or decelerating), it can be assumed with sufficient accuracy that $M_{hP} = M_{hT} = M_{hs}$ is achieved. The assumption is sufficiently accurate in the operating area where the torque transmitted through hydrodynamic coupling is larger enough than torque losses.

Characteristic points that define starting/stopping ($M_{hs} = M_{hsz}$; $\omega_{hs} = 0$) and nominal regimes ($M_{hs} = M_{hsn}$; $\omega_{hs} = \omega_{hsn}$) can be noticed on torque characteristic of a hydrodynamic coupling.

Torque characteristic of an operating device (Fig. 4) shows the value of the torque that has to be brought to the operating device for its stationary rotation. Two characteristic points can be noticed on the torque characteristic: starting/stopping regime ($\omega_{ru} = 0$; $M_{ru} = M_{ruz}$) and nominal regime ($\omega_{ru} = \omega_{run}$; $M_{ru} = M_{run}$).

---

[1] Nominal operating regime as a rule represents the recommended operating regime.

[#] The parabola of similarity is the curve connecting the points with equal efficiency.

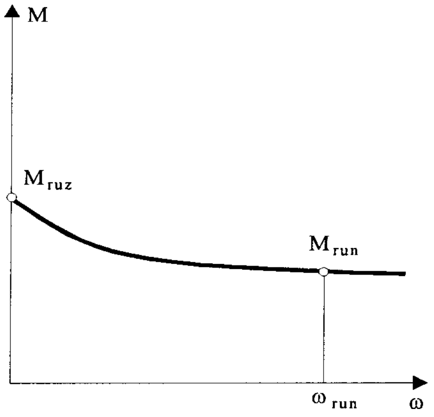


Fig. 4. Torque characteristic of an operating device

At the initial moment, angular velocities of motor shaft and output hydrodynamic coupling shaft are zero ($\omega_1 = 0$), motor torque is equal to the starting torque $M_m = M_{mz}$ and output hydrodynamic coupling shaft is resting ($\omega_2 = 0$; $M_2 = 0$). One part of motor torque M_m is needed for accelerating the motor shaft, pump section and corresponding part of operating fluid in hydrodynamic coupling, but larger torque part is delivered to turbine section of hydrodynamic coupling as torque M_{hs}. The value of M_{hs} depends on input (ω_1) and output (ω_2) angular velocities. If these angular velocities are zero ($\omega_1 = \omega_2 = 0$) then hydrodynamic coupling torque is also zero ($M_{hs} = 0$). As angular velocity of input shaft is increasing, non-zero torque appears at the output shaft of the hydrodynamic coupling. It Fig. 3 they are marked as stopping torque M_{hsz}. As long as their value is smaller than the initial torque of operating device M_{ruz} , output shaft will be in rest. After the torque M_{hs} becomes larger than operating device torque M_{ru}, output shaft of the hydrodynamic coupling will start running. The torque at the moment of output shaft starting is defined with: $\omega_2 = 0$; $M_{hs} = M_{ruz}$; $\omega_j = \omega_j^*$ and $M_m = M_m^*$. Since that torque, both shafts are rotating until the end of starting process, I.e. until the angular velocities become stable. This steady state regime is defined with: $\omega = \omega_1 = \omega_{mn}$, $M_m = M_{mn}$; $M_{hs} = M_1 = M_2 = M_{\mathrm{mn}}$; $\omega_{\mathrm{hs}} = \omega_2 = \omega_{\mathrm{hsn}}$; $\omega_{ru} = \omega_2 = \omega_{run}$ and $M_{ru} = M_{run}$. It is assumed that elements of operating system are previously correctly chosen, so that in reached steady state regime all elements are operating in nominal regimes.

3. MATHEMATICAL MODEL OF DRIVING MECHANISM

Formerly described driving mechanism is shown in Fig. 5 as two shafts with reduced masses. Shaft 1 is rotating at angular velocity ω_1, shaft 2 at angular velocity ω_2, where $\omega_1 > \omega_2$.

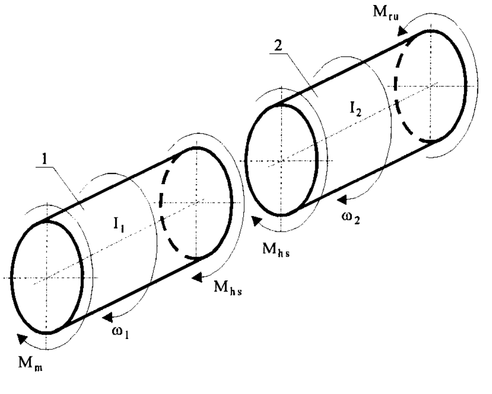


Fig. 5. Mechanical model driving mechanism
1. Shaft 1
2. Shaft 2

Rotating masses of electric motor, pump section and corresponding part of operating fluid of hydrodynamic coupling are reduced to shaft 1. Masses of output shaft, turbine section and corresponding part of operating fluid of hydrodynamic coupling, as well as the rotating parts of operating device are reduced to shaft 2. Elastic and dumping characteristics of remainder elements in driving mechanism are neglected.

The driving motor torque M_m acts at the left end of shaft 1. The dependence of this torque on angular velocity ω_1 is shown in Fig. 2. Torque M_{hs} acts at the right end of the shaft 1. This torque is transmitted to shaft 2. The dependence of this torque on the angular velocities ω_1 and ω_2 is shown in Fig. 3. At the right end of shaft 2 acts torque M_{ru}. This torque opposes to the hydrodynamic coupling torque. The dependence of this torque on angular velocity ω_2 is shown in Fig. 4.

Following equations can be written for shafts 1 and 2:

$$M_m = M_{i1} = M_{hs} \tag{1}$$

$$M_{hs} - M_{i2} = M_{ru} \tag{2}$$

Inertial torque for shafts 1 and 2:

$$M_{i1} = I_1 \dot{\omega}_1 = I_1 = I_1 \frac{\partial \omega_1}{\partial t} \tag{3}$$

$$M_{i2} = I_2 \dot{\omega}_2 = I_2 \frac{\partial \omega_2}{\partial t} \tag{4}$$

Substituting (1) and (2) into (3) and (4), the next expressions are obtained:

$$M_m - I_1 \frac{\partial \omega_1}{\partial t} = M_{hs} \tag{5}$$

$$M_{hs} - I_2 \frac{\partial \omega_2}{\partial t} = M_{ru}\,. \tag{6}$$

4. SOLVING OF MATHEMATICAL MODEL

Equations (5) and (6) will be solved graphically as it is shown in Fig. 6. The torque characteristics of driving mechanism with hydrodynamic coupling are shown in Fig. 6 from left to right.

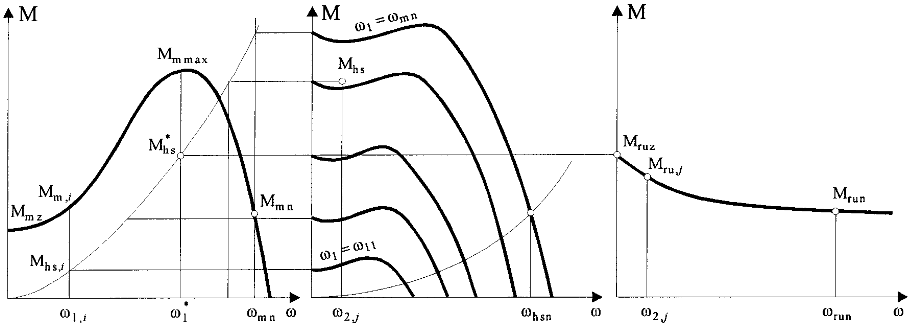


Fig. 6. Graphical solving of torque equations

The characteristic of hydrodynamic coupling torque M_{hsz} is added to the diagram of electric motor torque characteristic. This characteristic shows the dependence of torque M_{hs} when the output angular velocity ω_2 is zero, i.e. when the ratio of output and input velocity is zero ($\omega_2/\omega_1 = 0$).

The point with coordinates ω_1^* and M_{hsz}^* can be easily noticed on M_{hsz} characteristic. This point defines the operating regime when the output torque of the hydrodynamic coupling is equal to the torque of the operating device. Than one obtains $\omega_1 = \omega_1^*$; $M_{hs} = M_{hsz}^* = M_{ruz}$; $\omega_2 = 0$. Until this moment, only shaft 1 is running, therefore only equation (5) should be solved. In order to solve equation (5), it has to be assumed that starting process is divided into series of time intervals with constant angular acceleration, motor torque and hydrodynamic coupling torque, i.e. according to the method of the lower rectangles. As the parameters are constant during the each time interval, the number of intervals should be large enough.

In regard to the presented assumption, differential equation (5) becomes an ordinary linear equation:

$$M_m - I_1 \frac{\Delta\omega_1}{\Delta t} = M_{hs} \tag{7}$$

Equation (7) is solved upon Δt for known $\Delta\omega_1$. For time interval i, in which the angular velocity increases from $\Delta\omega_{1,i-1}$ to $\omega_{1,i}$, it is:

$$\Delta t_i = \frac{\omega_{1,i} - \omega_{1,i-1}}{M_{m,i-1} - M_{hs,i-1}} I_1 \tag{8}$$

When all the time intervals and increments of angular velocity are known, it is possible to evaluate angular acceleration in each time interval:

$$\dot{\omega}_{1,i} = \frac{\omega_{1,i} - \omega_{1,i-1}}{\Delta t_i} I_1 \tag{9}$$

The calculation procedure over the intervals is presented in a more detailed form in paper [1].

The duration of starting interval of shaft 1, i.e. electric motor, until the angular velocity ω_1^* is reached, is simply the sum of time intervals:

$$\Delta t^* = \sum_{i=1}^{i=i^*} \Delta t_i \tag{10}$$

From the moment when torque $M_{hs} = M_{ruz}$ appears at the hydrodynamic coupling exit shaft, and shaft 1 reaches angular velocity $\omega_1 = \omega_1^*$, shaft 2 starts to run. Now both shafts are accelerating and the starting period is finished when angular velocity $\omega_1 = \omega_{mn}$ is reached. This starting period is also divided into series of time intervals with constant angular acceleration, driving motor torque, hydrodynamic coupling torque and operating device torque. In Fig. 6 only two intervals are shown.

Once again, differential equations (5) and (6) become ordinary linear equations:

$$M_m - I_1 \frac{\Delta\omega_1}{\Delta t} = M_{hs} \tag{7}$$

$$M_{hs} - I_2 \frac{\Delta\omega_2}{\Delta t} = M_{ru} \,. \tag{11}$$

Equations (7) and (11) are solved in the following way. At first, the value of Δt is found for known $\Delta\omega_1$ from (7), i.e. (8). For known Δt, the value of $\Delta\omega_2$ can be obtained from (11), i.e. (12), using the already mentioned method of lower rectangles:

$$\Delta\omega_{2,j} = \frac{M_{hs,i^*+j-1} - M_{ru,i^*+j-1}}{I_2} \Delta t_{i^*+j} \tag{12}$$

Now, the values of M_m, M_{hs} and M_{ru} can be calculated for known values of $\Delta\omega_2$ and $\Delta\omega_1$, i.e. ω_2 and ω_1. These values are used in next iteration, etc.

Described procedure should be carried on until the stationary angular velocity of operating device is reached. Generally, it can be considered that the calculation is finished when iteration error is less than ±5%.

The duration of starting interval of shaft 2, i.e. operating device, until the angular velocity ω_{run} is reached, is simply the sum of time intervals :

$$\Delta t^{**} = \sum_{j=1} \Delta t_j \,. \tag{13}$$

5. SOLUTION ANALYSIS

The presented calculation can be used for finding starting interval duration of driving mechanism as well as for finding the dependence of input and output torque, input and output angular velocity and power losses on the accelerating time.

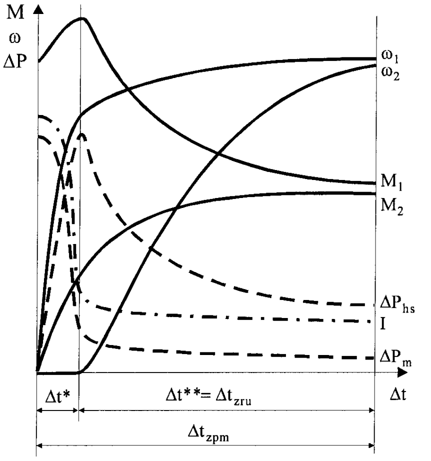


Fig. 7. Dependence of input and output torque,input and output angular velocity, current and power losses on the starting period of hydrodynamic coupling.

The starting interval of a driving motor is:

$$\Delta t_{zpm} = \Delta t^* + \Delta t^{**} \tag{14}$$

The starting interval of an operating device is:

$$\Delta t_{zrn} = \Delta t^{**} \tag{15}$$

The dependence of input and output torque, input and output angular velocities and power loss are shown in Fig. 7.

The power loss in hydrodynamic coupling can be evaluated from (16) [2], [3]:

$$\Delta P_{hs} = P_1 - P_2 = M_1 \cdot \omega_1 - M_2 \cdot \omega_2 \tag{16}$$

The power loss in electric motor mostly depends on the square of electric current and can be evaluated as it is shown, for example in [4].

Analysis of diagram shown in Fig. 7 shows that the highest loading of the electric motor and hydrodynamic coupling is obtained during the starting period. Because of that, for previously chosen electric motor driving, the hydrodynamic coupling has to be chosen so to enable fast starting of the motor. Furthermore, chosen hydrodynamic coupling has to enable appropriate starting of the operating device. This starting period has to be long enough to avoid too high loading of the operating device, but short enough to enable its fast start.

6. CONCLUSION

The paper illustrates the starting regime calculation of a hydrodynamic coupling. As a result of calculation, the starting intervals of operating device and electric motor were evaluated. Transient regime from the initial moment of the electric motor starting to the beginning of the steady-state operating regime was considered.

The presented calculation is easy to use. Ordinary linear equations are used for finding the solutions. Besides that, calculation is economical and does not require special skills (a technician equipped with pocket calculator can perform the calculation).

The calculation enables finding the graphical dependence of input and output torque, input and output angular velocities and power losses in electric motor and hydrodynamic coupling on the accelerating time. These diagrams can be used for finding mechanical and thermal loading of driving mechanism, i.e. for confirming the adequate choice of the hydrodynamic coupling.

REFERENCES

1. D. Uzelac, D. Knežević, R. Šostakov: *Calculation of starting period of hydrodynamic coupling*, HIPNEF '96, Beograd, 1996.
2. O. B. Aremenko: *Ograničivajuščie gidrodinamičeskie mufti*, Mašinostroenie, Moskva, 1970.
3. M. Wolf, *Strömungskupplungen und Strömungswandler*, Springer-Verlag, Berlin, 1962.
4. B. Jurković: *Elektromotorni pogoni*, Školska knjiga, Zagreb, 1987.
5. R. Šostakov, J. Vladić, N. Brkljač, D. Uzelac: *Berechnung der Anlaufdauer eines Antriebssystems mit hydrodynamischer Kupplung aufgrund des vereinigten M-n Diagrams*, XIV International Conference on Material Handling and Warehousing, Beograd, 1996.
6. R. Šostakov, D. Uzelac, N. Brkljač, *Determining the Starting Regime Duration of a Driving Mechanism with a Hydrodynamic Coupling or Transformer*, 4th International Scientific and Professional Conference "Power Source and Transfer '97", Podgorica - Budva, 1997.
7. D. Uzelac, R. Šostakov, S. Tašin: *Starting Regimes of a Hydrodynamic Coupling*, 4th International Scientific and Professional Conference "Power Source and Transfer '97", Podgorica - Budva, 1997.
8. D. Uzelac, *Hydraulic transmissions*, Lectures, FTN, Novi Sad, 1996.

ZALET ELEKTROMOTORNOG POGONA PREKO HIDRODINAMIČKE SPOJNICE

Dušan Uzelac, Rastislav Šostakov, Slobodan Tašin

Zalet elektromotornog pogona preko hidrodinamičke spojnice je prelazni režim rada od uključivanja pogonskog elektromotora da postizanja stacionamog stanja. Zalet je važno proučiti, jer se iz njega mogu odrediti veličine bitne za izbor elemenata izvora i prenosa snage. Analizom *zaleta moguće je odrediti vreme zaleta pogonskcg motora, tj. proveriti da li je one dovoljno kratkc. Moguće je odrediti i vreme zaleta radnog uređaja, tj. da li je one dovoljno dugo. Takođe je moguće odrediti toplotno opterećenje elemenata pogona i njihovo mehaničko opterećenje. Primer jednostavnog i dovoljno tačnog proračuna kojim se određuju režimi zaleta hidrodinamičke spojnice dat je u ovom radu.*

Ključne reči: *prenosnici snage, hidrodinamičke spojnice, prelazni režim rada*