A design proposal of driving system for roof segments and gantry crane of ecological floating dock

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ABSTRACT

In the conceptual design of an ecological floating dock, has been assumed to be applied a roof system consisted of six movable segments whose aim is to shelter dock's working space from environmental influence. The dock has to be also equipped with a gantry crane. Each of the devices is fitted with a traction system whose drive is the subject of this paper. The driving system consisted of synchronous electric motors with external frequency control of their rotational speed, is proposed. Such system may ensure the same rotational speed at both supports, unambiguously determined by voltage frequency and independent of load. The solution could make it possible to avoid dangerous skewing displacements of the structures on rail tracks during service. Additionally, a simplified procedure of determining the main loads necessary for calculation and selection of the devices and traction systems is also presented.

Keywords : floating dock, shipboard equipment, gantry crane driving mechanisms, systems of movable roof segments

INTRODUCTION

The traction system provided for the roof segments and gantry crane of the floating dock has to displace them almost horizontally by driving a number of rail wheels. If the moving route is horizontal frictional tractive adhesion of the wheels is sufficient to initiate their moving.

An important problem which may occur in operation of the dock's roof and gantry crane is their skewing on the railway, that, in consequence, produces additional resistance against motion or also inadmissible deformation of structures.

The phenomenon can occur due to non-uniform driving the traction wheels on both rails (small differences of mechanical characteristics of driving motors can lead to different lengths of way done by the wheels), wear of the wheels, non-parallel position of rails making wheel flanges to act, as well as a non-uniform wind pressure distribution. It is hence necessary to apply devices protecting against excessive skewing. The permissible value of skewing depends on design arrangement of mounting the roof structure onto traction wheel units, as well as roof's rigidity (in the case of gantry cranes the estimated permissible advance of one support by the other amounts to about 4 % of span of the crane bridge [1]).

As the dock's roof elements and gantry crane are similar to each other regarding their construction it is reasonable to propose the same design solution for their driving systems, which will lead to a decrease of unit cost because of application of a greater number of the same units. The dock's roof as well as the gantry crane is of a large span therefore it requires providing for separate traction drives on both side. Such drive should be so designed as to ensure synchronous run or also to control and eliminate possible skewings (i.e. keeping them within permissible limits). Moreover both the roof segment and crane should have an additional protection against strong wind effects, e.g. devices for jamming their structure onto traction rails.

One of the considered design proposals of the traction mechanism's driving system for the roof segments and gantry crane of the ecological floating dock in question is presented below.

TRACTION MECHANISM'S DRIVING SYSTEM FOR ROOF AND CRANE, FITTED WITH SYNCHRONOUS MOTORS AND FREQUENCY CONTROL OF THEIR ROTATIONAL SPEED

Electrical drive is assumed to be applied for the traction systems of roof elements and gantry crane. This solution is dominating in applications of the kind and its common use results from the following merits :

- easiness of energy supply
- large starting and braking moments
- easiness of remote control
- easiness of reversing and possible speed control
- lack of energy consumption during breaks in operation
- easiness of maintenance, replacement of parts, and service
- great flexibility of permissible load-carrying ability.

The proposed traction mechanism's driving system is of individual type because of a large span of roof segments and crane, it means that separate driving units are provided for both supports. In comparison with common driving systems an important advantage of the individual one is the lack of any long transmission shaft.

Load equalizers should be applied in order to obtain uniform distribution of pressure loads on traction wheels, and only a half of number of traction wheels would be driven.

The driving system's operation could be based on application of an electric asynchronous motor. In this case classical solutions aimed at synchronization of running the traction mechanisms of both supports could be :

- electric shaft (simplified one or fitted with auxiliary motors)
- measuring synchro-tie.

However it should be stressed that a modern solution which makes it possible to precisely control advance speed of both supports, is the driving system fitted with synchronous motors and frequency control of their rotational speed.

Synchronous motor

Synchronous motors are first of all applied to machines requiring a constant rotational speed. They are alternating current (AC) motors in which the following relationship occurs between the current frequency *f* in their armature and the rotational speed *n* of their rotors :

$$f = p \cdot n \quad [\text{Hz}]$$

where :

f – current frequency [Hz]
n – rotational speed [rps]
p – number of pole pairs of motor,

hence, respectively :

$$n = \frac{f}{p} \quad [\text{rps}]$$

$$\omega = 2 \cdot \pi \cdot n \quad [\text{rad/s}]$$

The motor's torque is :

$$M_s = \frac{P}{\omega} = \frac{P}{2 \cdot \pi \cdot n} \quad [\text{Nm}]$$

where :

M_s – shaft driving moment [Nm]
P – power output [W]
ω – angular speed [rad/s]
n – rotational speed [rps].

The property of concurrence of rotational speeds of motor shaft and magnetic field determines synchronous character of operation of the motor, which it should be brought in. Due to a large inertia moment of the motor's rotor its start-up appears difficult, that makes application of special starting methods necessary. The used solutions are as follows :

- asynchronous start-up
- start-up by using an auxiliary motor
- frequency-controlled start-up.

By applying the frequency control the problem of starting is solved in a natural way by gradual increasing supply current frequency and simultaneous maintaining synchronism of shaft rotation. For the frequency-controlled start-up a synchronous starting generator of the controlled voltage U and frequency *f*, or a controllable frequency converter is necessary. In the case of starting by means of the generator the motor's armature is connected with the starting generator, and exciter's winding with a constant voltage source. By increasing the generator's frequency from zero to its rated value the motor is driven into a synchronous speed. Next, the motor is synchronized with the electric supply network and after that it is switched off the starting generator and switched in the electric supply network.

Driving system based on synchronous motor with cycloconverter control (external control)

The cycloconverter-based systems are the systems used for speed control of synchronous motors (also asynchronous cage motors) by changing supply voltage frequency. This is the system in which rotational speed of synchronous motor is controlled externally. Such control is realized when the speed of rotating field, forced by the inverter, does not depend on a motor state but it is forced by an external control system. The so controlled motors maintain their initial features , i.e. the synchronous ones fall out of step under overload (but induction ones have a distinct point of falling out of step). A wide range of rotational speed control is available and reversible operation is possible both for motors and generators. Therefore it is possible to form mechanical characteristics of the drives in all four quadrants of the speed-moment reference system.

The cycloconverter is a direct frequency converter, being a set of thyristor rectifiers in which ignition angles vary in function of time with the period corresponding to a required initial frequency. Such operation is based on modulation of the voltage wave of 50 Hz by means of a control signal of a controllable frequency. The rotational speed control by changing supply voltage frequency is the most effective way to control AC motors.

The cycloconverter driving system based on a synchronous motor has very important merits in comparison with the systems based on direct current (DC) motors or asynchronous ones, namely :

- ❋ maintaining rotational speed constant and precise representing rotational speed by keeping it proportional to frequency of motor's supply voltage (setting-up the cycloconverter output frequency simultaneously means direct setting-up the rotational speed, that results from the synchronism principle: n = f/p). The advantage is especially valuable for the multi-motor driving system of traction mechanism for the roof segments and gantry crane in question, which has to satisfy the condition of equal running
- ❋ possible operation in both rotation directions
- ❋ a wide range of possible monitoring and control of important operational parameters of the drive
- ❋ large overload capacity
- ❋ high value of efficiency coefficient
- ❋ unlimited driving power
- ❋ low requirements for maintenance, hence a greater serviceability
- ❋ rotational speed not restricted by motor's design, on the contrary to the case of DC motors
- ❋ compliance with the redundancy principle by applying divided winding to the synchronous motor
- ❋ lower consumption of passive power (or even zero consumption of passive power).

The following features may be taken as disadvantages :

- ☆ high initial cost, (however in service, cycloconverters give measurable profits in comparison with the drives of other kinds in which static converters are applied)
- ☆ starting-up difficulties
- ☆ work at a lower electric supply frequency.

Work of such electric motors at a lower electric supply frequency is their basic design problem. Both synchronous and induction motors are designed for 50 Hz frequency, but 15 Hz frequency at the most is used for cycloconverter - based drives. So significantly lowered frequency means that simultaneously significant lowering the power output of the motor must happen due to the supply voltage dropping approximately proportional to the change of frequency. Hence a motor designed to develop a given power is capable of developing only 1/3 of its rated output when operating in conditions of cycloconverter-based driving system. It leads to greatly over-dimensioned gabarites of the motor.

Driving system based on synchronous motor with internal control

Another solution of synchronous motor control is internal control system. The synchronous motor supplied from the inverter tripped in function of rotor's position is called *the con-*

verter motor. The internal frequency control of rotational speed is characterized by that the rotating field velocity ω_S depends on motor's state e.g. its mechanical speed Ω, or on mutual position of resultants of the vectors Ψ_S and u_S. The internal control system makes unlocking a successive inverter's valve dependent on rotor's position. As a result, under greater loads the slowed-down rotor needs more time to cover the rotation angle within which the position indicator is able to send an impulse to initiate commutation. Therefore the period of alternating current delivered to stator's winding also increases which is equivalent to lowering the rotational speed. The converter motor cannot operate at extremely small speeds as then the induced rotation voltage is not sufficient to commutate inverter's valves.

Process of making the rotor rotating with 10% of the rated speed at which a sufficiently large rotation voltage is induced, is realized by breaking the current in the intermediate circuit. The current is then directed to the successive pair of inverter's valves, which connects the stator's winding strips whose resultant area in the gap moves by 60% towards the motor revolution direction. The internal control system is favourable when applied to a single synchronous motor, as it ensures its stable operation and eliminates the danger of falling-out of step because the motor's voltage frequency adjusts itself to the applied load.

DETERMINATION OF MAIN LOADS

The simplified scheme of determination of the main loads necessary to calculate and select devices and traction mechanisms of a roof segment are presented below. A similar scheme may be used to determine main loads applied to the gantry crane.

Calculation of pressure loads on traction wheels

The pressure loads on traction wheels are calculated by taking into account distribution of deadweight of the structure, mechanisms, equipment and snow. Lateral wind pressure forces may also appear out of the plane of axes of the traction wheels, hence some changes of the pressure loads on traction wheels in function of changes of sense of the loads may occur. Since head shields are assumed to be applied on the dock's heads the wind pressure forces acting both on the lateral area of the roof and its front areas should be accounted for.

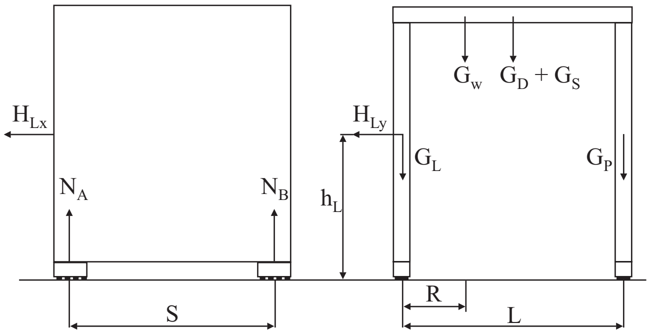

Fig. *Distribution of forces acting on roof segment*

Vertical forces acting on one side
of the roof segment (support) are as follows :

$$\sum G_L = G_w \cdot \left(\frac{L-R}{L}\right) + \frac{G_D}{2} + \frac{G_S}{2} + G_L$$

$$\sum G_P = G_w \cdot \left(\frac{R}{L}\right) + \frac{G_D}{2} + \frac{G_S}{2} + G_P$$

where :

G_D – load resulting from mass of the roof

G_L – load on the left-side support

G_P – load on the right-side support

G_w – load resulting from equipment elements of the roof

G_S – load resulting from mass of snow or ice.

Horizontal forces acting on one side
of the roof segment (support) are as follows :

$$\sum H_L = H_L$$

$$H_L = \overrightarrow{H_{Lx}} + \overrightarrow{H_{Ly}}$$

$$\sum H_P = H_P$$

$$H_P = \overrightarrow{H_{Px}} + \overrightarrow{H_{Py}}$$

Pressure loads acting on the equalizers
of the left-side support :

$$N_{AL} = \frac{\sum G_L}{2} + \overrightarrow{H_{Ly}} \cdot \frac{h_L}{l} + \overrightarrow{H_{Lx}} \cdot \frac{h_L}{s}$$

$$N_{BL} = \frac{\sum G_L}{2} + \overrightarrow{H_{Ly}} \cdot \frac{h_L}{l} + \overrightarrow{H_{Lx}} \cdot \frac{h_L}{s}$$

Pressure loads acting on the equalizers
of the right-side support :

$$N_{AP} = \frac{\sum G_P}{2} + \overrightarrow{H_{Py}} \cdot \frac{h_P}{l} + \overrightarrow{H_{Px}} \cdot \frac{h_P}{s}$$

$$N_{BP} = \frac{\sum G_P}{2} + \overrightarrow{H_{Py}} \cdot \frac{h_P}{l} + \overrightarrow{H_{Px}} \cdot \frac{h_P}{s}$$

Pressure loads falling to one traction wheel
(for 4-wheel equalizing system) :

$$N_1 = 0.25 \cdot N_{AL}$$

$$N_2 = 0.25 \cdot N_{BL}$$

$$N_3 = 0.25 \cdot N_{AP}$$

$$N_4 = 0.25 \cdot N_{BP}$$

Calculation of tractive resistance

Tractive resistance of flanged wheels :

$$W_t = (1+\beta)\sum G \frac{2f + \mu d}{D}$$

where :

β – coefficient accounting for tractive resistance resulting from action of flange

G – pressure load on traction wheels

f – shift of reaction

μ – friction factor in bearings

d – axle diameter

D – traction wheel diameter.

Resistance of rising :

$$W_{wz} = \pm \sum G \sin\alpha$$

where :

α – railway inclination angle

G – total load

Resistance resulting from wind pressure
applied to a movable object :

$$W_w = \pm\, cAq$$

where :

c – flow resistance coefficient

A – windage area
q – specific wind pressure load.

Total tractive resistance :

$$W_c = (1+\beta)\sum G\frac{2f+\mu d}{D} \pm \sum G\sin\alpha \pm cAq$$

Calculation of power output of driving motor

Power output of the driving motor :

$$N_u = \frac{W_c \cdot V_j}{\eta \cdot z}$$

where :

W_c – total tractive resistance of the roof segment
V_j – traction speed of the roof segment
η – efficiency of mechanism
z – number of driving motors.

Checking the protection against slip of wheels

The traction mechanism cannot cause the traction wheel's slip on the rail during start-ups and brakings. During wheel slip in the start-up phase circumferential wear of the wheel and local one of the rail occurs as well as an initial skewing the structure may happen. During braking, wheel slip causes local wear of the wheel as well as it can cause the roof segment falling-out of the rails which results from high kinetic energy of the roof's tractive motion and skewing due to slip of a wheel. Therefore the wheel slip during braking is very dangerous. Checking the protection against wheel's slipping is thereby the checking if the motor's power output is correctly determined as just its surplus can cause the danger of wheel slip. The traction mechanism of a small height is assumed hence horizontal forces do not influence pressure loads on the wheels during start-ups.

The condition of starting-up without slip of wheels

$$T \geq B + W'$$

where :

T – wheel-rail friction without wheel slip
B – inertia force
W' – total tractive resistance reduced by rolling resistance of bearings of driven wheels. The condition results from the fact that friction moment in bearings is internal one balanced by motor's torque but not by wheel-rail adhesive force.

$$W' = W_c - \sum F_n \mu\frac{d}{D}$$

where :

W_c – total tractive resistance
F_n – pressure load on driven wheels
μ – friction factor in bearings
d – axle diameter
D – traction wheel diameter.

Inertia force at the maximum acceleration not causing wheel slip :

$$B = \frac{\sum G}{g} a_{max}$$

where :

$\sum G$ – total load
a_{max} – the maximum acceleration not causing wheel slip
g – gravity acceleration.

Friction force :

$$T = \mu_1 \sum F_n$$

where :

μ_1 – friction factor.

Under the assumption that :

$$\sum F_n = \sum F_o = \frac{\sum G}{2}$$

where :

$\sum F_n$ – pressure load on driven wheels
$\sum F_o$ – pressure load on not driven wheels
$\sum G$ – total load.

by substituting the expressions to the formula :

$$T \geq B + W'$$

$$\mu_1\frac{\sum G}{2} \geq \frac{\sum G}{g} a_{max} +$$

$$+\left[(1+\beta)\sum G\frac{2f+\mu d}{D} - \sum G\sin\alpha - cAq - \frac{\sum G}{2}\mu\frac{d}{D}\right]$$

and after transformations the following is obtained :

$$a_{max} \leq g\left[\frac{\mu_1}{2} - \frac{2f(1+\beta)}{D} - \frac{\mu d(0.5+\beta)}{D} + \sin\alpha + \frac{cAq}{\sum G}\right]$$

Traction mechanism cannot generate any greater acceleration than that above given, therefore :

$$a = \frac{\varepsilon}{i}\frac{D}{2} \leq a_{max}$$

$$\varepsilon = \frac{M_d}{J_{zr}} = \frac{4g(M_{max} \pm M_o)}{GD_{zr}^2} = \frac{4g(mM_{zn} \pm M_o)}{GD_{zr}^2}$$

$$a_{max} \geq \frac{2g(mM_{zn} \pm M_o)D}{GD_{zr}^2 i}$$

$$\frac{2g(mM_{zn} \pm M_o)D}{GD_{zr}^2 i} \leq$$

$$\leq g\left[\frac{\mu_1}{2} - \frac{2f(1+\beta)}{D} - \frac{\mu d(0.5+\beta)}{D} + \sin\alpha + \frac{cAq}{\sum G}\right]$$

hence after transformations the following is determined :

$$M_{zn} \leq \left[\frac{\mu_1}{2} - \frac{2f(1+\beta)}{D} - \frac{\mu d(0.5+\beta)}{D} + \sin\alpha + \frac{cAq}{\sum G}\right] \cdot$$

$$\cdot \frac{GD_{zr}^2 i}{2Dm} \pm \frac{M_o}{m}$$

where :

M_{zn} – rated torque of driving motor
GD_{zr}^2 – equivalent flywheel effect reduced to high-speed shaft
D/2 = r – radius of inertia
M_d – dynamic moment
M_{max} – maximum moment
m – mass of moving elements
M_o – active driving moment

The condition of braking without slip of wheels :

$$T \geq B - W''$$

where :

T – wheel-rail friction without wheel slip
B – inertia force
W” – tractive resistance – total resistance calculated without accounting for the friction in bearings of driven wheels as well as friction of wheel flanges because the latter reduces the danger of wheel slip during braking.

$$W" = \frac{W_c}{1+\beta} - \sum F_n \cdot \frac{\mu d}{D}$$

The inertia force at the maximum deceleration (braking) not causing wheel slip :

$$B = \frac{\sum G}{g} a_{maxh}$$

Friction force :

$$T = \mu_1 \sum F_n$$

Under the assumption that :

$$\sum F_n = \sum F_o = \frac{\sum G}{2}$$

by substituting the expressions to the formula :

$$T \geq B - W”$$

first the following :

$$\mu_1 \frac{\sum G}{2} \geq \frac{\sum G}{g} a_{maxh} +$$

$$- \left[\frac{(1+\beta)\sum G \frac{2f+\mu d}{D} - \sum G \sin\alpha - cAq}{1+\beta} - \frac{\sum G}{2} \cdot \frac{\mu d}{D} \right]$$

hence after transformations
the condition is achieved as follows :

$$a_{maxh} \leq g \left[\frac{\mu_1}{2} + \frac{2f+0.5\mu d}{D} - \frac{\sin\alpha}{1+\beta} - \frac{cAq}{\sum G(1+\beta)} \right]$$

The braking moment is to be greater than the permissible one determined by means of the above given maximum value of limiting deceleration. With the braking moment coacts the tractive resistance moment which should be determined without accounting for friction of wheel flanges :

$$M'_{oh} = \frac{W_o D}{2i} \eta_h$$

$$W_o = \sum G \frac{2f + \mu d}{D}$$

$$M_H + M'_{oh} \leq J_{zr} \varepsilon_{maxh}$$

$$M_H \leq \frac{GD^2_{zrh}}{4g} \frac{2a_{maxh} i}{D} - M'_{oh}$$

hence after substitution the following is obtained :

$$M_H \leq \frac{GD^2_{zrh} i}{2D} \left[\frac{\mu_1}{2} + \frac{2f+0.5\mu d}{D} - \frac{\sin\alpha}{1+\beta} - \frac{cAq}{\sum G(1+\beta)} \right] +$$

$$- \frac{\sum G(2f+\mu d)\eta_h}{2i}$$

where :

M_H – braking moment
M'_{oh} – tractive resistance moment
W_o – tractive resistance without accounting for friction of flanges.

CONCLUSIONS

- The driving system based on synchronous electric motors and external frequency control of their rotational speed seems to be, as far as its operational merits are concerned, the most favourable solution of the traction mechanism for the roof segments and gantry crane in question. The internal control is favourable in the case of application of one motor, but in the considered case its cooperation with a greater number of motors is needed.

- The external control ensures that the driving motors maintain an important feature of synchronous motors : their rotational speed is unambiguously determined by supply voltage frequency and not dependent on their load. As the shaft load increases the load angle δ_i also increases, and if the load becomes excessive the motor will – at the angle close to $\delta = \pi/2$ – fall out of step. Therefore any overload resulting from skewing the roof segment or crane structure on the railway will make their drive switching off and their stopping due to triggering off the brakes fitted with electromagnetic releases. Such system will ensure parallel run of the shafts of multi-motor driving system as well as protection against consequences of skewing the structure.

- In order to monitor and supervise motion of the roof segments and gantry crane the system should be additionally equipped with measuring, signaling and control devices.

- The selected traction mechanism driven by synchronous motors will ensure the mobility of roof segments and fulfilment of the above mentioned requirements; however it should be stressed that its initial cost will be higher than that of another solution based on a ship docking system (described in a separate report), considered by the authors.

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