Influence of wind on the movement of the load

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Abstract. This paper presents theoretical considerations and numerical calculations concerning wind influence on the movement of the load during working cycle. During the test, the load is treated as a rigid body. The first part of this work includes the analysis of the aluminium cubical model of the load, which could move only in one plane, striving to increase the stability of motion and prevent vibrations. Numerical analysis was performed in Matlab/Simulink program and compared with experimental results, which were carried out in a low speed wind tunnel equipped with PIV system. The study was carried out for two cases: with and without seeding. The second part of this work includes the application of this research method for analysing the laboratory mobile crane’s duty cycle. Numerical simulations were carried out on a modified simulation model. The sample numerical results present the trajectory and positions of the load carried on the non-deformable rope taking into account the wind influence.

1. Introduction
The problem of load movement analysis is a complex issue in the field of multi-body dynamics of machines and transport devices. Movement of the carried load has a significant impact on the duty cycle of these devices and the cargo fluctuations can lead, in extreme cases, to loss of stability. This work concerns the analysis of the movement of the load carried by a mobile crane taking into account wind influence. The phenomenon of wind effect is often neglected during the analysis of the cargo motion [1]. This interaction can cause failures of cranes due to wind effect [2, 3]. In the literature and norms there are specific critical wind values at which the transporting device can work. The influence of stability and external factors on its dynamic behavior were discussed in works [4-6].

The movement of the load in the form of a rigid body, taking into account the influence of wind pressure, has been analyzed in this work. In the first part of the work, the load movement was considered as the pendulum motion on a rigid rope [7] with the impact of external forces. The simulation research have been compared with the results of an experiment conducted in a wind tunnel and the PIV method. This method makes it possible to measure and visualize the velocity of the flow field using laser light [8]. In the second part, the equations determined in the first part were used to analyze the crane’s duty cycle. The solution of the initial problem of the load movement was numerically calculated using the ode45 procedure in the Matlab/Simulink program. This function implements the Runge-Kutta method with a variable time step for efficient numerical calculation. The necessary condition of using this procedure is to provide system into the form of first order differential equations [9].
2. Analytical description of the problem

The phenomenon of aerodynamic drag has often been overlooked during research on the transport of loads. The wind influence on the movement of the load can be taken into account by adding additional external force $F_w$ [10]:

$$F_w = \frac{1}{2} \rho_{air} A V^2 C_F \tag{1}$$

where: $\rho_{air}$ is the density of air, $A$ is a reference area, $V$ is the wind velocity relative to object and $C_F$ is a dimensionless force coefficient. Simulation model that takes into account the impact of wind during the working cycle is shown in Figure 1a.

The cargo model with the movable local rectangular coordinate system (C) and forces acting on it during duty cycle is shown in Figure 1b. The load is suspended on a non-deformable line $l$. In order to define the position of the load during working cycle, it is necessary to determine the orientation of the C-coordinate system with respect to the global system. For this purpose, it was necessary to use Bryant angles, which allow determining the angular velocities and accelerations associated with the mobile coordinate system [4, 5].

![Figure 1](image1.png)

Figure 1. a) Computational model of the load, b) Forces acting on the load

Components of vector $\omega$ in the moving coordinate system can be calculated from the formula:

$$\omega_i = \dot{\psi} \cos \theta \cos \Phi + \dot{\phi} \sin \Phi$$

$$\omega_j = \dot{\psi} \cos \theta \sin \Phi - \dot{\phi} \cos \Phi$$

$$\omega_k = \dot{\psi} \sin \theta + \dot{\phi} \tag{2a-c}$$

Rotation about a fixed point can be described by the vector equation [3]:

$$M_C = \frac{d}{dt} K_C, \tag{3}$$

where: $K_C$ - angular momentum vector which can be described as:

$$K_C = J_C \omega_C \tag{4}$$
where: \( J \) – moments of inertia matrix, \( \omega \) – absolute angular velocity of body rotation around its center of mass.

Using the second law of Newton’s dynamics, the vector of moments acting on a solid body can be written as [4]:

\[
M_C = r \times F,
\]

(5)

where: \( F \) – vector sum of the tension in the rope, force of inertia of the load and the wind force.

Dynamic equations of motion for the cargo, treated as a rigid body, can be presented in the form using Einstein’s summation convention [4, 5]:

\[
M_a = J_{\alpha\beta\gamma} \epsilon_{\beta\gamma\alpha} \omega_{\beta} J_{\alpha\mu} \omega_{\mu}, \quad \alpha = 1, 2, 3
\]

(6)

where: \( J \) is the moments of inertia matrix, and \( \epsilon_{\beta\gamma\alpha} \) is Ricci symbol.

Taking into account the angular velocities and accelerations of the load (2), moment components and their transformations (3), as well as forces acting on the load (4), a system of three second order differential equations is obtained:

\[
D \dot{X} = E.
\]

(7)

3. Applied research methods

Using the above relationships and introducing them to the simulation model [4], the initial-value problem of the cargo movement has been solved numerically in the Matlab/Simulink program. In the first phase the load motion was treated as the pendulum motion, that could move only in one plane. The load was suspended using a metal rod, which properties correspond to a non-deformable line [7]. The simulation results were compared with experimental results, which were conducted in a low speed wind tunnel equipped with a Particle Image Velocimetry (PIV) system. With use Particle Image Velocimetry can be measured instantaneous velocity distribution, vortex properties and calculate the forces acting on the object. Simulation parameters and material properties are shown in Table 1.

| Table 1. Material properties and simulation parameters\(^a\). |
|---------------------------------------------------------------|
| Mass of the load | Density of material load’s | Length of the line | Load dimensions | Dimensionless wind force coefficient | Wind velocity | Deflection of angle |
|------------------|----------------------------|-------------------|----------------|-------------------------------------|---------------|---------------------|
| 0.5kg            | 2800kg/m\(^3\)            | 0.18m             | 0.06x0.06x0.05m | 2.05                                | 0m/s, 6m/s, 12m/s | 7\(^\circ\), 21\(^\circ\) |

\(^a\) Constant and controlled temperature and humidity (for experimental results).

3.1. Simulation results

The initial numerical simulations were performed using Runge-Kutta fourth-order method. In order to solve the initial problem with this method of the movement, the previous formulas should be reduced to the system of first order differential equations by substitutions [4, 9]:

\[
X_1 = \psi_1, X_2 = \theta_2, X_3 = \phi_3, X_4 = \psi_1, X_5 = \dot{\theta}_2, X_6 = \dot{\phi}_3
\]

(8)

The movement of the pendulum with the length of \( l \) with the suspended mass \( m \) can be represented by the equation [7]:

\[
ml\ddot{\theta} = -mg \sin \theta
\]

(9)
The simulations were made for two values of deflection of an angle: 7° (Fig. 2) and 21° (Fig. 3). The motion of the lifted load was considered for the time $t = 5s$. Based on the performed test (frequency of vibrations), it can be concluded that the consideration of wind force has been correctly interpreted and implied. Due to the motion analysis in only one direction, only values of one Bryant angle variable were obtained ($\theta$).

3.2. Experimental results

The experimental tests, confirms the dynamic of load motion. Differences in results are caused by a different type of analyzed pendulum: mathematical and physical. During the experiments, the aluminum cuboidal load model could move only in one plane, like the pendulum. The PIV measurements were carried out for two inflow velocities 6 m/s and 12 m/s, with acquisition frequency 15 Hz and constant and controlled temperature and humidity. The equipment PIV parameters was described in [11]. Recorded data were processed with the use of the adaptive correlation algorithm and as a result, instantaneous vortices fields were achieved (Fig. 4).
The load motion is subject to friction and air drag (the cross-sectional area of the string and load), so the amplitude of it swings declines. Figure 5 presents the oscillations of longitudinal and perpendicular velocity components in point P (see Fig. 4) with respect to the time. The position of the point P is in front of the rotating load, which is rotating in plane parallel to the incoming velocity. As the load motion does the back and forth, the velocity is continuously changing. There will be times at which the velocity is a negative value (for moving leftward) and other times at which it will be a positive value (for moving rightward).

![Figure 5. Experimental PIV tests: the oscillations of a) longitudinal and b) transverse velocity components in point P.](image)

4. Application of the research method
The simulation model of a mobile crane was created in SolidWorks environment and transferred to Matlab/Simulink program using CAD process of implementation [4, 12]. SimMechanics models allow for tracking many parameters (trajectory, velocity or acceleration) of any elements of a complex system [12]. Thanks to this approach, it is possible to avoid a number of complex analytical calculations. Bryant angles and their related velocity to the OXYZ coordinate system were used to analyze the working cycle of mobile crane (Figure 6).

| Table 2. Material properties and simulation parameters. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mass of load    | Density of load’s material | Diameter of rope | Length of rope | Load dimensions | Dimensionless wind force coefficient | Wind velocity |
| 50kg            | 2800kg/m³        | 0.013m          | 1.5m           | 0.3x0.3x0.2m    | 2.05             | 0m/s, 6m/s, 12m/s |
Taking into account the equation of motion determined during the analysis of the pendulum, the system had to be supplemented with additional equations related to the mobile crane motion. System of equations of load motion carried by laboratory mobile crane [4]:

\[
\ddot{\xi} = a_{1XX} + \frac{\zeta}{\rho_1^2} \left[ \rho_1 \ddot{\rho}_1 + \dot{\rho}_1 + \xi a_{1XX} + \eta a_{1Z} + \zeta (a_{1Y} + g) - \left( \ddot{\xi} + \dot{\eta} + \dot{\zeta} \right) \right]
\]

\[
\ddot{\eta} = a_{1Z} + \frac{\eta}{\rho_1^2} \left[ \rho_1 \ddot{\rho}_1 + \dot{\rho}_1 + \xi a_{1X} + \eta a_{1Z} + \zeta (a_{1Y} + g) - \left( \ddot{\xi} + \dot{\eta} + \dot{\zeta} \right) \right] \quad (10a-c)
\]

\[
\ddot{\zeta} = a_{1Y} - g - \frac{\zeta}{\rho_1^2} \left[ \rho_1 \ddot{\rho}_1 + \dot{\rho}_1 + \xi a_{1X} + \eta a_{1Z} + \zeta (a_{1Y} + g) - \left( \ddot{\xi} + \dot{\eta} + \dot{\zeta} \right) \right]
\]

The analyzed motion began from zero initial conditions for the time equal 15s. Control function were adopted as a trapezoid pulses and start-up, steady and braking states were included. The working cycle included operation: boom inclination angle \((t_{\text{start}}=0s, t_{\text{stop}}=5s, v_{\text{max}}=0.08\text{rad/s})\), boom length changes \((t_{\text{start}}=5s, t_{\text{stop}}=10s, v_{\text{max}}=0.2\text{m/s})\) and 5s free oscillations of the lifted cargo. The initial problem was solved using ode 45 procedure in Matlab/Simulink enviroment.

**Figure 6. Simulation model of mobile crane**

**Figure 7.** Changes of: a) Bryant angles, b) generalized velocity \((V_w=0\text{m/s})\)
Based on the performed tests, it can be concluded that the wind force has a significant influence on the deflection of the cargo during its transfer and should not be neglected during research on the dynamics of the load. Variations in the trajectory and positioning of the load were also observed depending on the severity of the wind velocity. The greatest deflection of the cargo (when wind velocity is less or equal 6m/s) can be noticed at the free oscillations of the load (t=10s). When wind velocity is equal to 12m/s, the deflection is similar for all kinematic forces (Fig. 9). When the external force $F_w$ is equal to zero, deflection was noticed only in one direction caused by the kinematics exclusions (Fig. 7).

Figure 8. Changes of: a) Bryant angles, b) generalized velocity ($V_w=6m/s$)

Figure 9. Changes of: a) Bryant angles, b) generalized velocity ($V_w=12m/s$)

Figure 10. Dependency of wind velocity on trajectory of the load: a) X-coordinate, b) Y-coordinate

5. Conclusion
This paper describes a preliminary theoretical and computational considerations of load movement with wind influence. The cargo was treated as rigid body. First part involved the analysis of a simplified model that was presented as the mathematical pendulum motion. The obtained numerical results were compared with the experimental results. The second part presents the analysis of the mobile crane.
working cycle, which was the application of the previously determined equation of the load movement and the impact of wind velocity. During the research on the influence of the wind, a simplified model was adopted in which a reference area was assumed as a constant surface of a cuboid. Differences in the trajectory of the load were noted depending on the strength of the wind. The simulation model will be further developed by considering aerodynamic resistance and the friction forces in the joints, and aerodynamic parameters [13]. The presented simulation model may be the basis for the optimization of the load movement and positioning.

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