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MATHEMATICAL MODELS FOR THE VIRTUAL ANALYSIS OF THE MECHANICAL SYSTEMS – Part II

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Abstract: *The paper presents a method for the calculus of the motion of an mechanical system. For a system with five elements are obtained the relations for the calculus of the velocities and accelerations. The body free diagram is used to obtain the mbasket-ball player.*
Keywords: *mechanical system, mathematical model, virtual analysis*

1. INTRODUCTION

The paper presents a mechanical model for the study of the motion of a basket-ball player [1],[2],[3]. The model use the free body diagram of the system in order to obtain the motion equations for the player [4],[5],[6].

2. KINEMATICS AND CONSTRAINS

The positions of the mass center of the elements are:

$x_{C1} = \alpha_1 l_1 c_1$;

$y_{C1} = \alpha_1 l_1 s_1$;

$x_{C2} = l_1 c_1 + \alpha_2 l_2 c_2$;

$y_{C2} = l_1 s_1 + \alpha_2 l_2 s_2$;

$x_{C3} = l_1 c_1 + l_2 c_2 + \alpha_3 l_3 c_3$;

$y_{C3} = l_1 s_1 + l_2 s_2 + \alpha_3 l_3 s_3$;

$x_{C4} = l_1 c_1 + l_2 c_2 + l_3 c_3 + \alpha_4 l_4 c_4$;

$y_{C4} = l_1 s_1 + l_2 s_2 + l_3 s_3 + \alpha_4 l_4 s_4$;

$x_{C5} = l_1 c_1 + l_2 c_2 + l_3 c_3 + l_4 c_4 + \alpha_5 l_5 c_5$;

$y_{C5} = l_1 s_1 + l_2 s_2 + l_3 s_3 + l_4 s_4 + \alpha_5 l_5 s_5$;

$x_6 = l_1 c_1 + l_2 c_2 + l_3 c_3 + l_4 c_4 + l_5 c_5$;

$y_6 = l_1 s_1 + l_2 s_2 + l_3 s_3 + l_4 s_4 + l_5 s_5$;

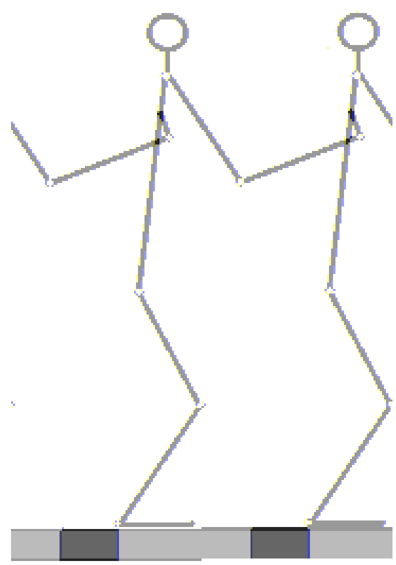

Figure 1. Mechanical model

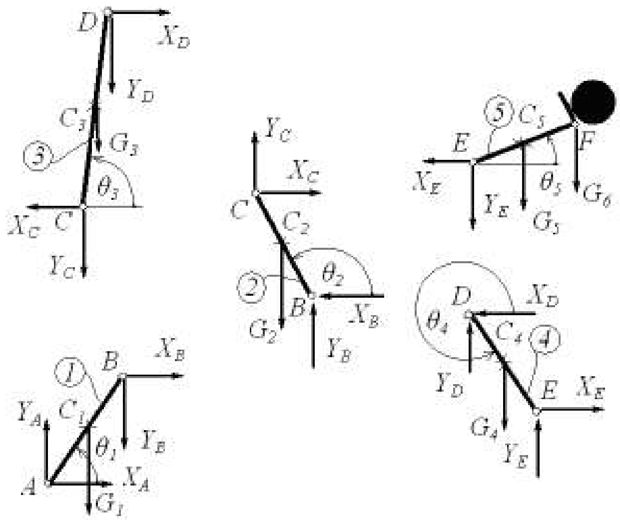

Figure 2. Free body diagram

$$\dot{x}_{C1} = -\alpha_1 l_1 s_1 \omega_1 \;;$$
$$\dot{y}_{C1} = \alpha_1 l_1 c_1 \omega_1 \;;$$
$$\dot{x}_{C2} = -l_1 s_1 \omega_1 - \alpha_2 l_2 s_2 \omega_2 \;;$$
$$\dot{y}_{C2} = l_1 c_1 \omega_1 + \alpha_2 l_2 c_2 \omega_2 \;;$$
$$\dot{x}_{C3} = -l_1 s_1 \omega_1 - l_2 s_2 \omega_2 - \alpha_3 l_3 s_3 \omega_3 \;;$$
$$\dot{y}_{C3} = l_1 c_1 \omega_1 + l_2 c_2 \omega_2 + \alpha_3 l_3 c_3 \omega_3 \;;$$
$$\dot{x}_{C4} = -l_1 s_1 \omega_1 - l_2 s_2 \omega_2 - l_3 s_3 \omega_3 - \alpha_4 l_4 s_4 \omega_4 \;;$$
$$\dot{y}_{C4} = l_1 c_1 \omega_1 + l_2 c_2 \omega_2 + l_3 c_3 \omega_3 + \alpha_4 l_4 c_4 \omega_4 \;;$$
$$\dot{x}_{C5} = -l_1 s_1 \omega_1 - l_2 s_2 \omega_2 - l_3 s_3 \omega_3 - l_4 s_4 \omega_4 - \alpha_5 l_5 s_5 \omega_5 \;;$$
$$\dot{y}_{C5} = l_1 c_1 \omega_1 + l_2 c_2 \omega_2 + l_3 c_3 \omega_3 + l_4 c_4 \omega_4 + \alpha_5 l_5 c_5 \omega_5 \;;$$
$$\dot{x}_6 = -l_1 s_1 \omega_1 - l_2 s_2 \omega_2 - l_3 s_3 \omega_3 - l_4 s_4 \omega_4 - l_5 s_5 \omega_5 \;;$$
$$\dot{y}_6 = l_1 c_1 \omega_1 + l_2 c_2 \omega_2 + l_3 c_3 \omega_3 + l_4 c_4 \omega_4 + l_5 c_5 \omega_5 \;;$$
$$\ddot{x}_{C1} = -\alpha_1 l_1 s_1 \varepsilon_1 - \alpha_1 l_1 c_1 \omega_1^2 \;;$$
$$\ddot{y}_{C1} = \alpha_1 l_1 c_1 \varepsilon_1 - \alpha_1 l_1 s_1 \omega_1^2 \;;$$
$$\ddot{x}_{C2} = -l_1 s_1 \varepsilon_1 - l_1 c_1 \omega_1^2 - \alpha_2 l_2 s_2 \varepsilon_2 - \alpha_2 l_2 c_2 \omega_2^2 \;;$$
$$\ddot{y}_{C2} = l_1 c_1 \varepsilon_1 - l_1 s_1 \omega_1^2 + \alpha_2 l_2 c_2 \varepsilon_2 - \alpha_2 l_2 s_2 \omega_2^2 \;;$$
$$\ddot{x}_{C3} = -l_1 s_1 \varepsilon_1 - l_1 c_1 \omega_1^2 - l_2 s_2 \varepsilon_2 - l_2 c_2 \omega_2^2 - \alpha_3 l_3 s_3 \varepsilon_3 - \alpha_3 l_3 c_3 \omega_3^2 \;;$$
$$\ddot{y}_{C3} = l_1 c_1 \varepsilon_1 - l_1 s_1 \omega_1^2 + l_2 c_2 \varepsilon_2 - l_2 s_2 \omega_2^2 + \alpha_3 l_3 c_3 \varepsilon_3 - \alpha_3 l_3 s_3 \omega_3^2 \;;$$
$$\ddot{x}_{C4} = -l_1 s_1 \varepsilon_1 - l_1 c_1 \omega_1^2 - l_2 s_2 \varepsilon_2 - l_2 c_2 \omega_2^2 - l_3 s_3 \varepsilon_3 - l_3 s_3 \omega_3^2 - \alpha_4 l_4 s_4 \varepsilon_4 - \alpha_4 l_4 c_4 \omega_4^2 \;;$$
$$\ddot{y}_{C4} = l_1 c_1 \varepsilon_1 - l_1 s_1 \omega_1^2 + l_2 c_2 \varepsilon_2 - l_2 s_2 \omega_2^2 + l_3 c_3 \varepsilon_3 - l_3 s_3 \omega_3^2 + \alpha_4 l_4 c_4 \varepsilon_4 - \alpha_4 l_4 s_4 \omega_4^2 \;;$$
$$\ddot{x}_{C5} = -l_1 s_1 \varepsilon_1 - l_1 c_1 \omega_1^2 - l_2 s_2 \varepsilon_2 - l_2 c_2 \omega_2^2 - l_3 s_3 \varepsilon_3 - l_3 c_3 \omega_3^2 - l_4 s_4 \varepsilon_4 - l_4 c_4 \omega_4^2 - \alpha_5 l_5 s_5 \varepsilon_5 - \alpha_5 l_5 c_5 \omega_5^2 \;;$$
$$\ddot{y}_{C5} = l_1 c_1 \varepsilon_1 - l_1 s_1 \omega_1^2 + l_2 c_2 \varepsilon_2 - l_2 s_2 \omega_2^2 + l_3 c_3 \varepsilon_3 - l_3 s_3 \omega_3^2 + l_4 c_4 \varepsilon_4 - l_4 s_4 \omega_4^2 + \alpha_5 l_5 c_5 \varepsilon_5 - \alpha_5 l_5 s_5 \omega_5^2 \;;$$

The previously obtained relation can be written as:

$$\begin{Bmatrix} \dot{x}_{c1} \\ \dot{y}_{C1} \\ \omega_1 \\ \dot{x}_{c2} \\ \dot{y}_{c2} \\ \omega_2 \\ \dot{x}_{c3} \\ \dot{y}_{c3} \\ \omega_3 \\ \dot{x}_{c4} \\ \dot{y}_{c4} \\ \omega_4 \\ \dot{x}_{c5} \\ \dot{y}_{c5} \\ \omega_5 \\ \dot{x}_6 \\ \dot{y}_6 \end{Bmatrix} = \begin{bmatrix} -\alpha_1 l_1 s_1 & 0 & 0 & 0 & 0 \\ \alpha_1 l_1 c_1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ -l_1 s_1 & -\alpha_2 l_2 s_2 & 0 & 0 & 0 \\ l_1 c_1 & \alpha_2 l_2 c_2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -l_1 s_1 & -l_2 s_2 & -\alpha_3 l_3 s_3 & 0 & 0 \\ l_1 c_1 & l_2 c_2 & \alpha_3 l_3 c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -\alpha_4 l_4 s_4 & 0 \\ l_1 c_1 & l_2 c_2 & l_3 c_3 & \alpha_4 l_4 c_4 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -l_4 s_4 & -\alpha_5 l_5 s_5 \\ l_1 c_1 & l_2 c_2 & l_3 c_3 & l_4 c_4 & \alpha_5 l_5 c_5 \\ 0 & 0 & 0 & 0 & 1 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -l_4 s_4 & -l_5 s_5 \\ l_1 c_1 & l_2 c_2 & l_3 c_3 & l_4 c_4 & l_5 c_5 \end{bmatrix} \begin{Bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \\ \omega_5 \end{Bmatrix}$$

and:

$$\begin{Bmatrix} \ddot{x}_{c1} \\ \ddot{y}_{C1} \\ \varepsilon_1 \\ \ddot{x}_{c2} \\ \ddot{y}_{c2} \\ \varepsilon_2 \\ \ddot{x}_{c3} \\ \ddot{y}_{c3} \\ \varepsilon_3 \\ \ddot{x}_{c4} \\ \ddot{y}_{c4} \\ \varepsilon_4 \\ \ddot{x}_{c5} \\ \ddot{y}_{c5} \\ \varepsilon_5 \end{Bmatrix} = \begin{bmatrix} -\alpha_1 l_1 s_1 & 0 & 0 & 0 & 0 \\ \alpha_1 l_1 c_1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ -l_1 s_1 & -\alpha_2 l_2 s_2 & 0 & 0 & 0 \\ l_1 c_1 & \alpha_2 l_2 c_2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -l_1 s_1 & -l_2 s_2 & -\alpha_3 l_3 s_3 & 0 & 0 \\ l_1 c_1 & l_2 c_2 & \alpha_3 l_3 c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -\alpha_4 l_4 s_4 & 0 \\ l_1 c_1 & l_2 c_2 & l_3 c_3 & \alpha_4 l_4 c_4 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -l_4 s_4 & -\alpha_5 l_5 s_5 \\ l_1 c_1 & l_2 c_2 & l_3 c_3 & l_4 c_4 & \alpha_5 l_5 c_5 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \end{Bmatrix} +$$

$$+ \begin{bmatrix} -\alpha_1 l_1 c_1 & 0 & 0 & 0 & 0 \\ -\alpha_1 l_1 s_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -l_1 c_1 & -\alpha_2 l_2 c_2 & 0 & 0 & 0 \\ -l_1 s_1 & -\alpha_2 l_2 s_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -l_1 c_1 & -l_2 c_2 & -\alpha_3 l_3 c_3 & 0 & 0 \\ -l_1 s_1 & -l_2 s_2 & -\alpha_3 l_3 s_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -l_1 c_1 & -l_2 c_2 & -l_3 c_3 & -\alpha_4 l_4 c_4 & 0 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -\alpha_4 l_4 s_4 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -l_1 c_1 & -l_2 c_2 & -l_3 c_3 & -l_4 c_4 & -\alpha_5 l_5 c_5 \\ -l_1 s_1 & -l_2 s_2 & -l_3 s_3 & -l_4 s_4 & -\alpha_5 l_5 s_5 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \\ \omega_5^2 \\ \omega_6^2 \end{Bmatrix}$$

$$\{a\} = [A_1]\{\varepsilon\} + [A_2]\{\omega^2\}.$$

3. DYNAMICS AND MOTION EQUATIONS

If we denote with:

$$[m]=\begin{bmatrix} m_1 &&&&&&&&&&&&&& \\ & m_1 &&&&&&&&&&&&& \\ && J_1 &&&&&&&&&&&& \\ &&& m_2 &&&&&&&& 0 &&& \\ &&&& m_2 &&&&&&&&&& \\ &&&&& J_2 &&&&&&&&& \\ &&&&&& m_3 &&&&&&&& \\ &&&&&&& m_3 &&&&&&& \\ &&&&&&&& J_3 &&&&&& \\ &&&&&&&&& m_4 &&&&& \\ &&&&&&&&&& m_4 &&&& \\ &&&& 0 &&&&&&& J_4 &&& \\ &&&&&&&&&&&& m_5 && \\ &&&&&&&&&&&&& m_5 & \\ &&&&&&&&&&&&&& J_5 \end{bmatrix}$$

The inertia matrix, the motion equations are:

$$[m]\{a\}=\{Q\},$$

or, if we take into account the form of acceleration:

$$[m]\left([A_1]\{\varepsilon\}+[A_2]\{\omega^2\}\right)=\{Q\}$$

If we premultiply the system with $[A_1]^T$ we have:

$$[M]=[A_1]^T[m][A_1]$$

where the elements of the $[M]$ are:

$$M_{11}=(m_1\alpha_1^2+m_2+m_3+m_4+m_5)l_1^2+J_1$$
$$M_{12}=l_1l_2c_{2-1}(\alpha_2m_2+m_3+m_4+m_5) \quad ;$$
$$M_{13}=l_1l_3c_{3-1}(\alpha_3m_3+m_4+m_5) \quad ;$$
$$M_{14}=l_1l_4c_{4-1}(\alpha_4m_4+m_5) \quad ; \quad M_{15}=l_1l_5c_{5-1}(\alpha_5m_5) \quad ;$$
$$M_{22}=(\alpha_2^2m_2+m_3+m_4+m_5)l_2^2+J_2 \quad ;$$
$$M_{23}=l_2l_3c_{3-2}(\alpha_3m_3+m_4+m_5) \quad ;$$
$$M_{24}=l_2l_4c_{4-2}(\alpha_4m_4+m_5);M_{25}=l_2l_5c_{5-2}(\alpha_5m_5) \quad ;$$
$$M_{33}=(\alpha_3^2m_3+m_4+m_5)l_3^2+J_3 \quad ;$$
$$M_{34}=l_3l_4c_{4-3}(\alpha_4m_4+m_5) \quad ; \quad M_{35}=l_3l_5c_{5-3}(\alpha_5m_5) \quad ;$$
$$M_{44}=(\alpha_4^2m_4+m_5)l_4^2+J_4 \quad ; \quad M_{35}=l_4l_5c_{5-4}(\alpha_5m_5) \quad ;$$
$$M_{55}=(\alpha_5^2m_5)l_5^2+J_5 \quad ;$$

If we denote:

$$[M']=[A_1]^T[m][A_2]$$

we can to obtain the element of the $[M']$ matrix:

$M'_{11}=0 \quad ; \quad M'_{12}=(\alpha_2m_2+m_3+m_4+m_5)l_1l_2s_{1-2} \quad ;$

$M'_{13}=(\alpha_3m_3+m_4+m_5)l_1l_3s_{1-2} \quad ; \quad M'_{14}=(\alpha_4m_4+m_5)l_1l_4s_{1-4} \quad ;$

$M'_{15}=\alpha_5m_5l_1l_5s_{1-5}$

$M'_{21} = (\alpha_2 m_1 + 3) m_1 l_1 l_2 s_{2-1}$; $M'_{22} = 0$; $M'_{23} = (\alpha_3 + 2) m_3 l_2 l_3 s_{2-3}$;
$M'_{24} = (\alpha_4 + 1) m_4 l_2 l_4 s_{2-4}$; $M'_{25} = \alpha_5 m_5 l_2 l_5 s_{2-5}$;
$M'_{31} = l_1 l_3 (\alpha_3 m_3 + m_4 + m_5) s_{3-1}$;
$M'_{32} = l_2 l_3 (\alpha_3 m_3 + m_4 + m_5) s_{3-2}$; $M'_{33} = 0$
$M'_{34} = l_3 l_4 (\alpha_4 m_4 + m_5) s_{3-4}$; $M'_{35} = \alpha_5 m_5 l_1 l_5 s_{3-5}$
$M'_{41} = l_1 l_4 (\alpha_4 m_4 + m_5) s_{4-1}$; $M'_{42} = l_2 l_4 (\alpha_4 m_4 + m_5) s_{4-2}$;
$M'_{43} = l_3 l_4 (\alpha_4 m_4 + m_5) s_{4-3}$; $M'_{44} = 0$; $M'_{45} = \alpha_5 m_5 l_4 l_5 s_{4-5}$
$M'_{51} = l_1 l_5 (\alpha_5 m_5) s_{5-1}$; $M'_{52} = l_2 l_5 (\alpha_5 m_5) s_{5-2}$;
$M'_{53} = l_3 l_5 (\alpha_5 m_5) s_{5-3}$; $M'_{55} = 0$; $M'_{54} = \alpha_5 m_5 l_4 l_5 s_{5-4}$

$$[M'] = \begin{bmatrix} 0 & (\alpha_2 m_2 + m_3 + m_4 + m_5) l_1 l_2 s_{1-2} & (\alpha_3 m_3 + m_4 + m_5) l_1 l_3 s_{1-2} & (\alpha_4 m_4 + m_5) l_1 l_4 s_{1-4} & \alpha_5 m_5 l_1 l_5 s_{1-5} \\ (\alpha_2 m_2 + m_3 + m_4 + m_5) l_1 l_2 s_{2-1} & 0 & (\alpha_3 m_3 + m_4 + m_5) l_2 l_3 s_{2-3} & l_2 l_4 (\alpha_4 m_4 + m_5) s_{2-4} & \alpha_5 m_5 l_2 l_5 s_{2-5} \\ l_1 l_3 (\alpha_3 m_3 + m_4 + m_5) s_{3-1} & l_2 l_3 (\alpha_3 m_3 + m_4 + m_5) s_{3-2} & 0 & (\alpha_4 m_4 + m_5) l_3 l_4 s_{3-4} & \alpha_5 m_5 l_3 l_5 s_{3-5} \\ l_1 l_4 (\alpha_4 m_4 + m_5) s_{4-1} & l_2 l_4 (\alpha_4 m_4 + m_5) s_{4-2} & l_3 l_4 (\alpha_4 m_4 + m_5) s_{4-3} & 0 & \alpha_5 m_5 l_4 l_5 s_{4-5} \\ l_1 l_5 (\alpha_5 m_5) s_{5-1} & l_2 l_5 (\alpha_5 m_5) s_{5-2} & l_3 l_5 (\alpha_5 m_5) s_{5-3} & \alpha_5 m_5 l_4 l_5 s_{5-4} & 0 \end{bmatrix}$$

Matrix $[M']$ is skew-symmetric.
The loads vector is:

$$\{Q\} = \begin{Bmatrix} X_A + X_B \\ Y_A - Y_B - G_1 \\ M_1 + X_A \alpha_1 l_1 s_1 - X_B (1-\alpha_1) l_1 s_1 - Y_A \alpha_1 l_1 c_1 - Y_B (1-\alpha_1) l_1 c_1 \\ -X_B + X_C \\ Y_B + Y_C - G_2 \\ M_2 - X_B \alpha_2 l_2 s_2 - X_C (1-\alpha_2) l_2 s_2 + Y_B \alpha_2 l_2 c_2 - Y_C (1-\alpha_2) l_2 c_2 \\ -X_C + X_D \\ -Y_C - Y_D - G_3 \\ M_3 - X_C \alpha_3 l_3 s_3 - X_D (1-\alpha_3) l_3 s_3 + Y_C \alpha_3 l_3 c_3 - Y_D (1-\alpha_3) l_3 c_3 \\ X_E - X_D \\ Y_E + Y_D - G_4 \\ M_4 + X_D \alpha_4 l_4 s_4 + X_E (1-\alpha_4) l_4 s_4 - Y_D \alpha_4 l_4 c_4 - Y_E (1-\alpha_4) l_4 c_4 \\ -X_E \\ -Y_E - G_5 - G_6 \\ M_5 - X_E \alpha_5 l_5 s_5 + Y_E \alpha_5 l_5 c_5 \end{Bmatrix}$$

If we premultiply this vector with $[A_1]^T$ we obtain:

$$\{Q'\} = [A]^T \{Q\} = \begin{Bmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \\ M_5 \end{Bmatrix} - \begin{Bmatrix} l_1 c_1 (\alpha_1 G_1 + G_2 + G_3 + G_4 + G_5 + G_6) \\ l_2 c_2 (\alpha_2 G_2 + G_3 + G_4 + G_5 + G_6) \\ l_3 c_3 (\alpha_3 G_3 + G_4 + G_5 + G_6) \\ l_4 c_4 (\alpha_4 G_4 + G_5 + G_6) \\ l_5 c_5 \alpha_5 (G_5 + G_6) \end{Bmatrix} = \{M^{ext}\} - \{M_G\}$$

It results the motion equations:

$$[M]\{\varepsilon\} + [M']\{\omega^2\} = [A_1]^T \{Q\}$$

or:

$$[M]\{\varepsilon\} + [M']\{\omega^2\} = \{M^{ext}\} - \{M_G\}$$

The vector of the external moments become:

$$\{M^{ext}\} = [M]\{\varepsilon\} + [M']\{\omega^2\} + \{M_G\}\ .$$

To compute the normal force acting on the horizontal plane it is necessary to sum the equations 2, 5, 8, 11, 14.
To do this we premultiply the system with:

$$\{YA\} = [0\quad 1\quad 0\quad 0\quad 1\quad 0\quad 0\quad 1\quad 0\quad 0\quad 1\quad 0\quad 0\quad 1\quad 0]$$

$$\{YA\}[m][A_1]\{\varepsilon\} + \{YA\}[m][A_2]\{\omega^2\} = \{YA\}\{Q\}$$

from where:

$$Y_A = G_1 + G_2 + G_3 + G_4 + G_5 + \{YA\}[m][A_1]\{\varepsilon\} + \{YA\}[m][A_2]\{\omega^2\}\ .$$

4. CONCLUSIONS

The measurement made with the Kistler table show a good agreement between the computed results and the experimental results.

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