DYNAMIC CHARACTERISTICS OF THE KARAKURI TRANSPORT TROLLEY

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Abstract
Karakuri is a mechanical device that utilizes natural physical phenomena (most frequently gravity force and electromagnetism) and elemental mechanisms (cams, springs, levers, rollers etc.) to perform handling operations in a less-energy or low-energy mode. Karakuri mechanisms may be utilized for handling of individual objects (e.g. product or component) or substances in packaging (e.g. animal fodder in bags). The paper deals with the dynamic behaviour of the karakuri transport trolley that uses accumulation of potential energy in compression springs. The presented research was focused on the basic speed-time and distance-time characteristics of the specific karakuri trolley that has significant potential for use in agriculture.

Key words: karakuri, trolley, transport, mechanism, distance, speed.

INTRODUCTION

The Japanese word „karakuri“ means a mechanical device to trick, or take a person by surprise. Central to the karakuri philosophy is concealment of technology, to evoke feelings and emotions, and a sense of hidden inner magic (MURATA and KATAYAMA, 2010, KATAYAMA et al. 2014). Traditional application of karakuri mechanisms are unique Japanese karakuri dolls (see Fig. 1). The karakuri tradition continues to influence the Japanese view of robots, robotics, low cost automation or lean manufacturing (OLSON, 2000). Karakuri devices are now used to make production or handling operations easier and more ergonomic and to increase productivity or decrease operational costs. A significant characteristic of karakuri devices is their minimal impact on the environment because they consume little or no energy. During last two decades karakuri-based devices were designed and realized mainly in the automotive industry to save energy, to decrease work-load or to reduce time of production or handling operations. These (kaizen) activities are carried out mainly in progressive companies such as Toyota, Daikin, Aisin Seiki, Honda and other.

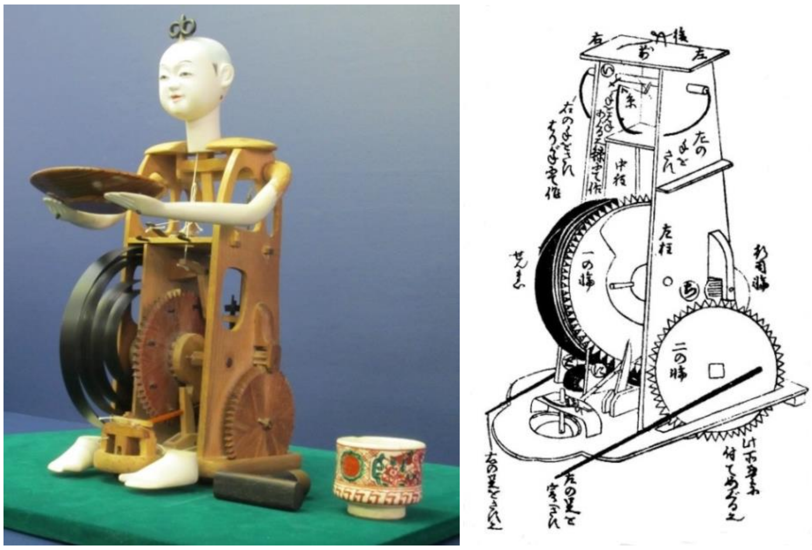

Fig. 1. – Mechanical moving doll (JAPAN TODAY,2015; KYOTO UNIVERSITY MUSEUM,2007)

These and other industrial enterprises use karakuri devices for the following purposes:

- Development, design and installation of low CO2 production technologies based on simplification, process streamlining or energy saving of moving parts.
- Improvement of energy use efficiency by recovery of wasted energy or storing of energy,
- Elimination of unnecessary or irrational (human) efforts.
- Utilization of unpowered technologies or technologies based on low-thrust operation energy.

From the point of view of unpowered technologies or technologies based on low-thrust operation energy we can use following elementary phenomena, mechanisms or components:

- Gravitation force (weight) - see Fig. 2
- Magnetic force
- Lever mechanism (seesaw mechanism)
- Cam mechanism
- Link mechanism
- Lock-up or release mechanism
- Spring
- Gear etc.

Fig. 2. – Simple karakuri structure for handling operation using gravitation force to provide efficient storage and easy unloading process (AMS, 2014)

In the field of agriculture, various (manual) handling operations must be performed through the year. Farmers have to move objects off the ground on a conveyor or move objects manually or by conveyor from point A to point B (e.g. handling of containers with vegetables or bags with compost or animal fodder). Most of these operations are trivial, repetitive, and require quite a lot of energy and power delivered by workers or technology (Fig. 3).

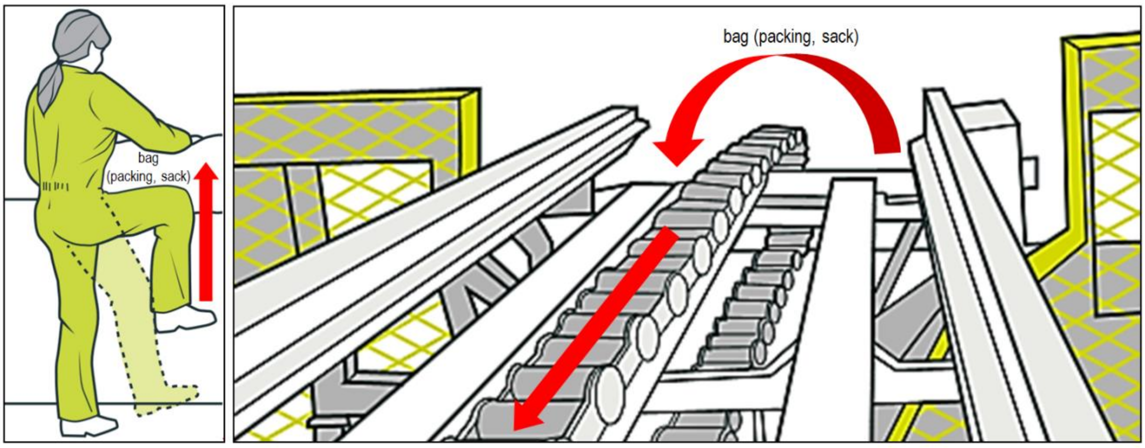

Fig. 3. – Examples of manual handling operation and chain conveyor used in agriculture(WORK SAFE NZ, 2014)

From the above it is clear the use of karakuri idea in agriculture and agricultural engineering is meaningful. Therefore the paper discusses one aspect of agricultural karakuri based device - the dynamic behavior of karakuri transport trolley. The goal of presented initial research was determination of time dependence for passed distance and trolley movement speed by defined transported weight (10 kg and 20 kg).

MATERIALS AND METHODS

The experimental trolley was designed for internal transport of objects between two places away 3.0 m (defined by kinematic design of gearbox). After insertion of transferred object to the box located on top of trolley the movement trolley is started (potential energy of transferred object is changed to kinematic energy). When the trolley drives off the distance it stops and after removal of the transported object from the box the trolley starts to move back to the starting position using the energy accumulated into the press springs during the forward movement.

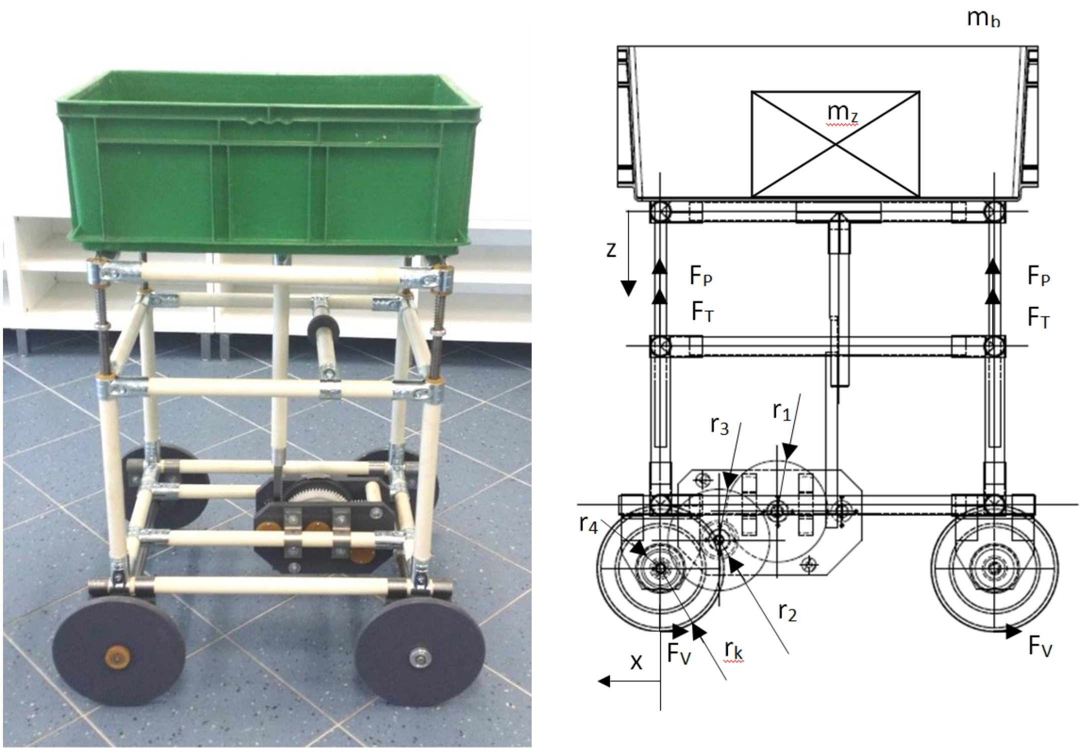

Fig. 4. – Design of the experimental karakuri trolley

Tab. 1. – Characteristics of trolley parts

Quantity	Name of part	Weight	MOI	Velocity		
				Shift X	Shift Z	Rotation
1	box + upper frame + cogged rack	m_b	-	$\dot{x}$	$\dot{z}$	0
1	transferred object	m_z	-	$\dot{x}$	$\dot{z}$	0
1	frame of trolley	m_p	-	$\dot{x}$	0	0
1	gear wheel Nr.1	m_1	J_1	$\dot{x}$	0	$\dot{\phi}_1$
1	gear wheel Nr.2	m_2	J_2	$\dot{x}$	0	$\dot{\phi}_2$
1	driven gear incl. pinion	ms_1	J_{s1}	$\dot{x}$	0	$\dot{\phi}_s$
1	not driven gear	ms_2	Js_2	$\dot{x}$	0	$\dot{\phi}s$

Total trolley weight:

$$m_{total} = m_b + m_z + m_p + m_1 + m_2 + m_{s1} + m_{s2} \qquad (1)$$

Dynamic characteristics were solved by defining a second order differential movement equations using the method of reduction of mass and force magnitudes on his frame. For solving mathematical equations software Maple were then used. Used method for reduction of mass and force magnitudes on frame is based on theory of kinetic energy change:

$$\frac{dK}{dt} = P \qquad (2)$$

$$^{*}K = \frac{1}{2} m_r \dot{x}^2 \ , \quad m_r = \text{konst.} \qquad (3)$$

$$\frac{^{*}dK}{dt} = m_r \ \dot{x} \ \ddot{x} \qquad (4)$$

Kinetic energy of karakuri trolley during his movement:

$$K = \frac{1}{2}(m_b+m_z)(\dot{x}^2+\dot{z}^2) + \frac{1}{2} m_p \dot{x}^2 + \frac{1}{2}(m_1+m_2+m_{s1}+m_{s2}) \dot{x}^2 + \frac{1}{2} J_1 \dot{\phi}_1^2 + \frac{1}{2} J_2 \dot{\phi}_2^2 + \frac{1}{2} J_{s1} \dot{\phi}_s^2 + \frac{1}{2} J_{s2} \dot{\phi}_s^2 \qquad (5)$$

Kinematic linkages:

$$\dot{x} = r_k \dot{\phi}_s \ ; \quad \dot{\phi}_s = \frac{1}{r_k} \dot{x} \qquad (6)$$

$$r_4 \dot{\phi}_s = - r_3 \dot{\phi}_2 \ ; \quad \dot{\phi}_2 = - \frac{r_4}{r_3} \dot{\phi}s \ ; \quad \dot{\phi}_2 = - \frac{r_4}{r_3 r_k} \dot{x} \qquad (7)$$

$$r_2 \dot{\phi}_2 = - r_1 \dot{\phi}_1 \ ; \quad \dot{\phi}_1 = - \frac{r_2}{r_1} \dot{\phi}_2 \ ; \quad \dot{\phi}_1 = - \frac{r_2 r_4}{r_1 r_3 r_k} \dot{x} \qquad (8)$$

$$r_1 \dot{\phi}_1 = \dot{z} \ ; \quad \dot{z} = - r_2 \dot{\phi}_2 \ ; \quad \dot{z} = \frac{r_2 r_4}{r_3 r_k} \dot{x} \qquad (9)$$

Afterwards:

$$K = \frac{1}{2}(m_b+m_z+m_p+m_1+m_2+m_{s1}+m_{s2}) \dot{x}^2 + \frac{1}{2}(m_b+m_z)\left(\frac{r_2 r_4}{r_3 r_k}\right)^2 \dot{x}^2 + \frac{1}{2} J_1 \left(\frac{r_2 r_4}{r_1 r_3 r_k}\right)^2 \dot{x}^2 + \frac{1}{2} J_2 \left(-\frac{r_4}{r_3 r_k}\right)^2 \dot{x}^2 + \frac{1}{2} J_{s1} \left(\frac{1}{r_k}\right)^2 \dot{x}^2 + \frac{1}{2} J_{s2} \left(\frac{1}{r_k}\right)^2 \dot{x}^2 = \frac{1}{2} m_p \dot{x}^2 \qquad (10)$$

$$m_p = (m_b+m_z)\left[1+\left(\frac{r_2 r_4}{r_3 r_k}\right)^2\right] + m_p+m_1+m_2+m_{s1}+m_{s2} + \frac{J_1}{r_k^2}\left(\frac{r_2 r_4}{r_1 r_3}\right)^2 + \frac{J_2}{r_k^2}\left(\frac{r_4}{r_3}\right)^2 + \frac{J_{s1}+J_{s2}}{r_k^2} \qquad (11)$$

Tab. 2. – Force and power effects on trolley

Force effect	Power effect
Gravity	$(m_b+m_z)\, g\, \dot{z}$
Spring forces	$- 4\, k\, z\, \dot{z}$
Friction	$- 4\, F_T\, \dot{z}$
Rolling resistance	$- 4 \frac{m_{celk}}{4}\, g\, \xi\, \dot{\phi}_s$

Total power:

$$P = [(m_b+m_z)\,g - 4\,k\,z - 4\,F_T]\,\dot{z} - m_{celk}\,g\,\xi\dot{\phi}_s \quad (12)$$

Transferred to $\dot{x}$:

$$P = \left\{[(m_b+m_z)\,g - 4\,k\,z - 4\,F_T]\,\frac{r_2 r_4}{r_3 r_k} - m_{celk}\,g\,\frac{\xi}{r_k}\right\}\dot{x} \quad (13)$$

The equation of motion:

$$\overset{*}{m}_r\,\dot{x}\,\ddot{x} = \left\{[(m_b+m_z)\,g - 4\,k\,z - 4\,F_T]\,\frac{r_2 r_4}{r_3 r_k} - m_{celk}\,g\,\frac{\xi}{r_k}\right\}\dot{x} \quad (14)$$

$$\overset{*}{m}_r\,\ddot{x} = [(m_b+m_z)\,g - 4\,F_T]\,\frac{r_2 r_4}{r_3 r_k} - m_{celk}\,g\,\frac{\xi}{r_k} - 4\,k\,\frac{r_2 r_4}{r_3 r_k}\,z \quad (15)$$

In which

$$z - z0 = \frac{r_2 r_4}{r_3 r_k}(x - x0) \quad (16)$$

Achieved:

$$\overset{*}{m}_r\,\ddot{x} + 4\,k\,\frac{r_2 r_4}{r_3 r_k}\left[z_0 + \frac{r_2 r_4}{r_3 r_k}(x - x_0)\right] = [(m_b+m_z)\,g - 4\,F_T]\,\frac{r_2 r_4}{r_3 r_k} - m_{celk}\,g\,\frac{\xi}{r_k}$$

$$m_r\,\ddot{x} + 4\,k\left(\frac{r_2 r_4}{r_3 r_k}\right)^2 x = [(m_b+m_z)\,g - 4\,F_T]\,\frac{r_2 r_4}{r_3 r_k} - m_{celk}\,g\,\frac{\xi}{r_k} - 4\,k\,\frac{r_2 r_4}{r_3 r_k}\left(z_0 - \frac{r_2 r_4}{r_3 r_k}x_0\right) \quad (17)$$

$$\text{difrov: } = m_R\left(\frac{d^2}{d_x^2}\,y(x)\right) + K\,y(x) = F_R \quad (18)$$

This motion equation (17) was solved using the specialized software MAPLE with graphic output for two different weights of transported object (10 kg and 20 kg) by inserting parameters obtained from created CATIA V5 (Dassault Systèmes') model of karakuri transport trolley:

m_p	- 29 kg
m_b	- 5 kg
m_z	- 10 kg
m_1	- 0.315 kg
m_2	- 0.345kg
m_{s1}	- 2.29kg
m_{s2}	- 2.26kg
r_1	- 0.07 m
r_2	- 0.02 m
r_3	- 0.07 m
r_4	- 0.02 m
r_k	- 0.11 m
J_1	- 0.00096 kgm^2
J_2	- 0.00098 kgm^2
J_{s1}	- 0.00445kgm^2
J_{s2}	- 0.00444kgm^2
F_t	- 5 N
ξ	- 0.0008 m
g	- 9.81m/s^2
k	- 2.5 N/mm
x_0	- 0.02 m
z_0	- 0.02 m

RESULTS AND DISCUSSION

The results obtained by experiments and by calculation of the motion equation (17) showed the following:

- Karakuri-based transport trolley was functional for object movement along a linear trajectory.
- Experimental karakuri transport trolley transported (moved) an object with 10 kg (20 kg) weight at a distance of 2 (3) m and returned back to starting position without additional energy supply.
- Both travelled distance and velocity of karakuri trolley depend on weight of transported object – see Fig. 5 and Fig. 6.
- Moving of trolley is uniformly accelerated for both variants of transported object weight (10 kg and 20 kg) – see Fig. 5 and Fig. 6.
- Velocity and acceleration of karakuri transport trolley was linear and depends on transported weight.

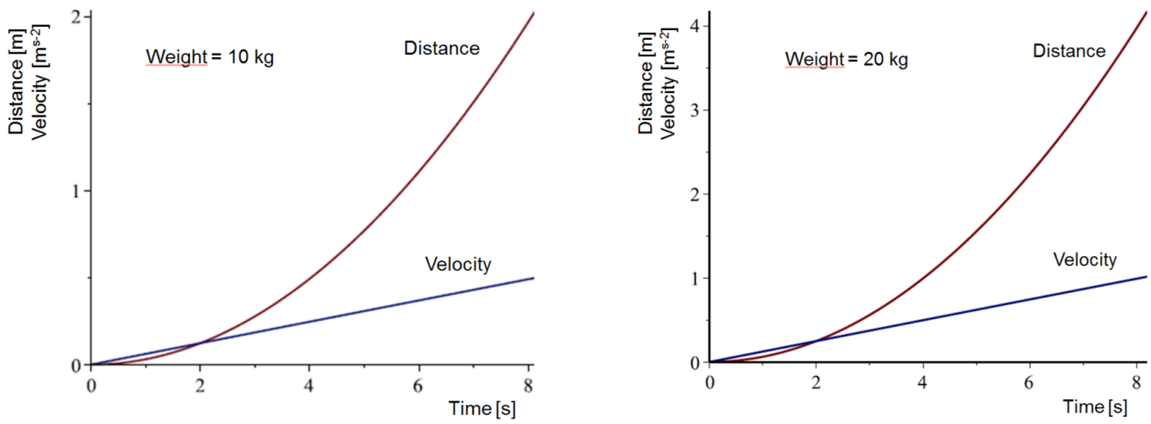

Fig. 5. – Diagram showing dependence of velocity and travelled distance on time (weight of transported object = 10 kg (left) and 20 kg (right)

The dynamic behaviour of the karakuri transport trolley has been tested through repeated physical measuring of time and distance by standard measuring instruments, calibrated scale and by video-records analysis. When comparing the calculated results with the measured values across distance 0 – 2 (3) m we can conclude that results obtained by calculation and by solving of motion equation well correspond to the real behaviour of the experimental karakuri trolley tested under practical conditions.

CONCLUSIONS

Karakuri transport trolley transported (moved) an object with common weight and dimensions at a distance of 2 (3) m and returned back to starting position without additional energy supply. The calculations confirmed the validity of the following differential equation for the proposed karakuri transport trolley:

Obtained results indicate there is potential for karakuri-based technical means in agriculture to save energy and human effort. For future development is necessary to deeply study the issues connected to karakuri mechanisms and present obtained results to agricultural engineers.

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REFERENCES

1. AMS, INC.: Available at: https://www.youtube.com/watch?v=hcDQ6BPWj90. Published 25 February 2014. Accessed 22 April 2016.
2. JAPAN TODAY: Japan Pavilion reopens in London with new exhibits, demonstrations. Available at:http://www.japantoday.com/category/national/view/japan-pavilion-reopens-in-london-with-new-exhibits-demonstrations. Published 26 October 2015. Accessed 22 April 2016.
3. KYOTO UNIVERSITY MUSEUM: Mechanisms of a tea serving doll. Available at: http://www.museum.kyoto-u.ac.jp/english/materials/chakumiDolleng.html. Published 1 November 2007. Accessed 22 April 2016.
4. WORK SAFE NZ: Preventing manual handling injuries on farms. Good Practice Guidelines. 1st ed., New Zealand, WorkSafe NZ 2014.
5. KATAYAMA, H., SAWA, K., HWANG, R., ISHIWATARI, N., & HAYASHI, N.: Analysis and classification of Karakuri technologies for reinforcement of their visibility, improvement and transferability: An attempt for enhancing lean management. In PICMET 2014 - Portland International Center for Management of Engineering and Technology, Proceedings: Infrastructure and Service Integration, 2014: 1895-1906.
6. OLSON, C. F.: Probabilistic self-localization for mobile robots. IEEE Transactions on Robotics and Automation 16(1), 2000: 55–66.
7. MURATA, K., KATAYAMA H.: Development of Kaizen case-base for effective technology transfer-A case of visual management technology, International Journal of Production Research (IJPR), Vol. 48, Issue 16, 2000: 4901-4917.

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