Impact of Inertial and External Forces on Joint Dynamics of Robotic Manipulator: Experimental Insights

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Abstract*—In this paper, the effect of the inertial and external forces applied on the links of the robotic manipulator is studied and investigated on the manipulator joints' parameters through experimental analysis. For this investigation and experiments, KUKA LWR manipulator is used and structured as a 2-DOF manipulator. Experimental work is carried out by commanding a sinusoidal joint motion to the two joints of the manipulator. Different scenarios are studied such as motion with free of collisions, motion with collision on the link between the two joints of the manipulator, motion with collision on the end-effector, and motions with different constant joint speeds. The diagrams of the position, velocity, acceleration, and torque of the manipulator joints are obtained and recorded from KUKA robot controller and then investigated and evaluated. The results reveal that during a motion free of collision, small spikes are found on the signals of the joint position, velocity, acceleration, and torques. These spikes resulted from the inertial forces applied on the joint. During a motion with collision, the signals of joint position, velocity, acceleration, and torque are highly affected due to the collision, inertial forces, and friction. During a collision on the end-effector, the torques of both joints are highly affected. During a collision on a link between the two joints, the torque of the first joint is highly affected, and the torque of the second joint is slightly affected. When the speed of the joint is increased, the torque signal is highly affected. These findings provide insights into the dynamic behavior of robotic manipulators under external forces, with implications for improving control algorithms and collision detection systems.

Keywords*—External Force, Inertial Force, Joint Dynamics, Position, Velocity, Acceleration, Torque, 2-DOF Robotic Manipulator, Experimental Work

I. Introduction

The robotic manipulator becomes very important machine in real life particularly in various fields like industry, agriculture, medicine, and service, [1]-[6]. The robotic manipulator is composed of links, motors, transmission systems such as gears or cams, and joints. When an external force or collision affected the links of the robot, vibration and deformation may happen and affect the robot itself, [7], [8]. Furthermore, this collision may negatively impact the stability and performance of the system. Therefore, a robust control system should be implemented to the robotic manipulator to maintain its stability and effectiveness under external disturbances.

A. The Estimation of External Force

Estimation of the external force affected by the robot manipulator was considered by previous researchers using different approaches. In [9], Colome et al. estimated the applied external forces on robot by using disturbance observer approach without any need to external sensors. Phong et al. [10] estimated the external forces applied on robot based on the joint torque sensors and based on a combined algorithm of time delay and input estimation. In [11], Pyrhönen et al. estimated the external forces applied on the robotic manipulator using the formulation of the semi recursive multibody. Optimization of particle swarm was used to estimate the external forces applied on robots, as presented in [12]. Neural networks based approaches were used to estimate the external forces or collisions with the robotic manipulators such as ref. [13]-[16].

B. The Study of Robotic Dynamics

The study of the dynamic of the robotic manipulator and the external of the applied forces on the joint's variables such as position, velocity, and torques, was investigated with previous researchers. In [17], a simulation study using MATLAB was implemented to investigate the effect of the external force on the joint position, velocity, acceleration, and computed torque of a 2-DOF planar manipulator. Luz Junior et al. [18] developed the dynamic model of 1-DOF robotic manipulator using a model of LuGre friction. In their work, the relation between the friction force and the position was presented and the diagrams of the friction torque and the joint position of the manipulator were shown. In [19], Ivanov et al. analyzed the dynamic model of the 3-DOF planar robotic manipulator. For their analysis, they used simulation environment (software package) to solve the nonlinearity of the model. Machine learning approaches were used for modelling the dynamics of the robotic manipulator as presented in [20]-[24].

C. The Main Chanllenges and Contributions

Previous studies indicate a need for deeper investigation into how external forces affect joint dynamics, including position, velocity, acceleration, and torque. Despite significant advancements, the impact of external forces and inertial effects on robotic manipulator dynamics remains inadequately explored through experimental verification.

Therefore, simulation works should be verified by the experimental and the real environment.

The main contribution and novelty of this paper is discussed in the following points:

- This paper provides experimental insights into the effects of inertial and external forces on robotic manipulator dynamics, leveraging real-world data from a KUKA LWR robot.
- The main aim of analyzing the impact of inertial and external forces on joint parameters is to improve manipulator performance under dynamic conditions.
- The effect of the inertial and external forces is investigated on the joints' positions, velocities, accelerations, and torques of the robotic manipulator.
- For this purpose, different scenarios are carried out and evaluated which include sinusoidal joint motion with free of collisions, sinusoidal motion with external force affected the different links of the manipulator, and motions with different constant joint speeds and collisions.
- KUKA LWR robot is used for the experiments and is structured as 2-DOF manipulator by activating only two joints (joint A3 and A5).
- KUKA LWR robot has joint position and torques sensors. Therefore, the joints' position, velocity, acceleration, and torque can be obtained and drawn based on KUKA robot controller (KRC). These parameters are investigated, discussed, and analyzed.

The rest of the paper is divided into the following sections. Section 2 shows the methodology and the different carried out scenarios and the experimental set-up. In Section 3, the obtained results are discussed and evaluated. Section 4 shows the key findings and Section 5 shows some future directions.

II. Materials and Methods

This section shows the methodology followed in this paper and the description of the used robot in the experiments. The dynamics of the robotic manipulator is given by the following equation, [25]-[27]:

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = \tau + \tau_{ext} \quad (1)$$

Where, $\theta, \dot{\theta}$, and $\ddot{\theta}$ are the joints position, velocity, and acceleration of the manipulators, $M(\theta)$ is the inertia matrix, $C(\theta,\dot{\theta})$ is the Coriolis and centrifugal matrix, $G(\theta)$ is the gravity vector of the manipulator links, τ are the actuator torque of the manipulator joints, and τ_{ext} is the external joint torque. The KUKA LWR robot is used for experimental work and is constructed to be a 2-DOF manipulator by activating only joint A3 (Joint 1) and joint A5 (Joint 2) of the robot. This robot is used for doing the experiments as shown in Fig. 1. The specifications of this robot are presented in Table 1.

Every joint of the KUKA LWR robot has joint position and torque sensors. The KR C2 lr control unit of the robot with fast research interface (FRI) [30] can give at one-millisecond the joint position, velocity, acceleration, measured torque, and the external torque estimation.

Six experiments are executed. The first three experiments are discussed as follows:

- Experiment 1: This experiment is performed by a sinusoidal motion for the manipulator joints without any collision on the robot links (baseline test).
- Experiment 2: This experiment is performed by executing a collision on the link between the two joints of the manipulator (link 1).
- Experiment 3: This experiment is performed by executing a collision on the end-effector of the robot (link 2).

In each of these three experiments, the position, velocity, acceleration, and the measured joint torques of the two joints are investigated and drawn.

The measured joint torques, and the external joint torques of the two joints are investigated during joints motion with constant speed. During the joints motion, a collision occurred on the link between the two joints of the manipulator. For this purpose, three other experiments are carried out as follows:

- Experiment 4: Joints motion with constant low speed (0.5rad/s) with collision on link between joints.
- Experiment 5: Joints motion with constant medium speed (1.0 rad/s) with collision on link between joints.
- Experiment 5: Joints motion with constant high speed (1.5 rad/s) with collision on link between joints.

The collisions on the various links of the robotic manipulator are carried out by the human hand. The collisions on the robot end-effector (link 2) and on the link between the two joints (link 1) are shown in Fig. 2. These mentioned experiments' setups are summarized and presented in Table 2. The results from the conducted experiments are presented in the next section.

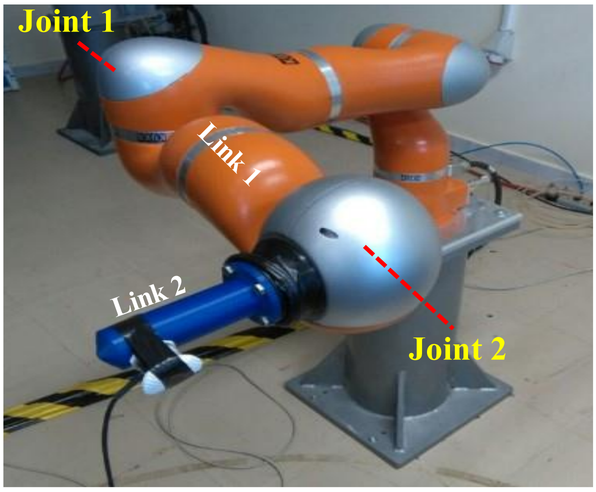
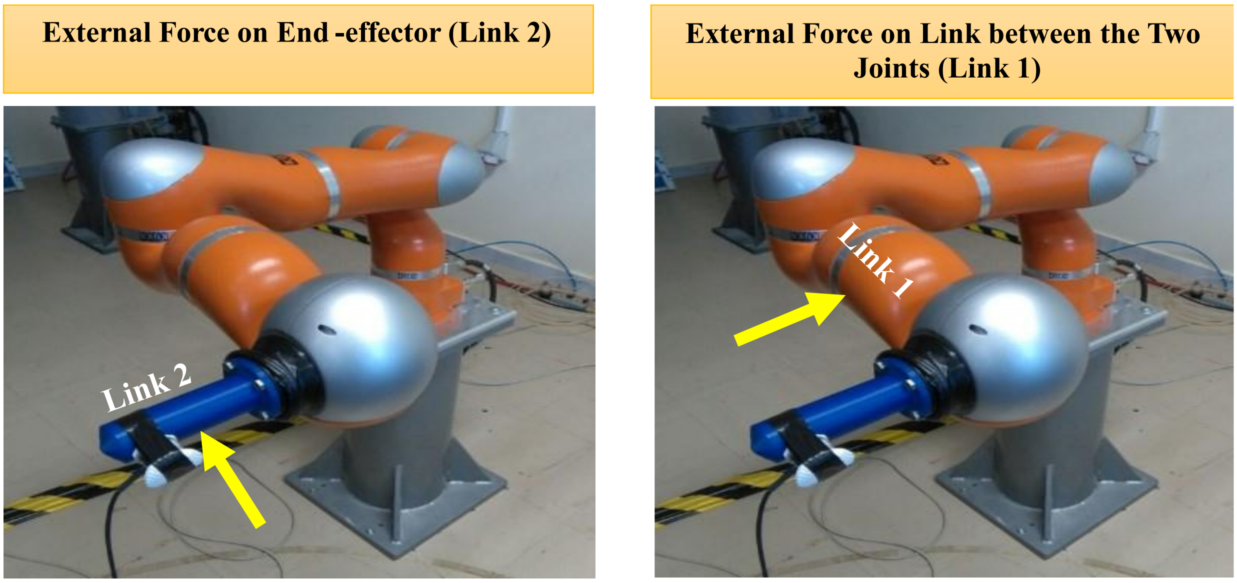


Fig. 1. The experimental setup. KUKA LWR is constructed as a 2-DOF manipulator by activating only joints A3 and A5

Table 1. The specifications of KUKA LWR robot used for the experiments, [28], [29]

Parameter	Value
Number of axes	7
Payload	7 kg
Repeatability (ISO 9283)	±0,05 mm
Controller	KR C2 lr
Weight (excl. controller) approximately	16 kg
Axis Data (Joints Range)	Axis 1 (A1): ± 170˚ Axis 2 (A2): ± 120˚ Axis 3 (A3): ± 170˚ Axis 4 (A4): ± 120˚ Axis 5 (A5): ± 170˚ Axis 6 (A6): ± 120˚ Axis 7 (A7): ± 170˚



(a) (b)

Fig. 2. The type of the collision/external force on the links of the manipulator. (a) The external force on the end-effector, and (b) the external force on the link between the two joints

Table 2. The experiments were carried out with the 2-DOF robotic manipulator

No.	Experiment Description	Joint 1 position range	Joint 2 position range	Benefits
1	Sinusoidal Motion without any collision	-90 deg to 90 deg	-90 deg to 90 deg	Check the joints parameters; position, velocity, acceleration, and torque
2	Sinusoidal Motion with collision on the link between the two joints (link 1)	-90 deg to 90 deg	-90 deg to 90 deg	Check the joints parameters; position, velocity, acceleration, and torque
3	Sinusoidal motion with collision on the end-effector (link 2)	-90 deg to 90 deg	-90 deg to 90 deg	Check the joints parameters; position, velocity, acceleration, and torque
4	One collision only between joints but in different configurations of the two links each time and this repeated three times. Constant speed of 0.5 rad/s for the two joints is used.	-90 deg to 90 deg	-90 deg to 90 deg	Check the measured/external joint torque from the controller for joint 2
5	One collision only between joints but in different configurations of the two links each time and this repeated three times. Constant speed of 1.0 rad/s for the two joints is used.	-90 deg to 90 deg	-90 deg to 90 deg	Check the measured/external joint torque from the controller for joint 2
6	One collision only between joints but in different configurations of the two links each time and this repeated three times. Constant speed of 1.5 rad/s for the two joints is used.	-90 deg to 90 deg	-90 deg to 90 deg	Check the measured/external joint torque from the controller for joint 2

III. Experimental Results

This section presents the results of the mentioned experiments in the previous section. The first three experiments are executed. In these experiments, a sinusoidal motion is commanded to the two joints of the manipulator. The first experiment is motion free of any collision. The second experiment is conducting a collision on the link between the two joints (link 1). The third experiment by conducting a collision on the end-effector (link 2). The diagrams of joints positions, velocities, accelerations and the measured joint torques resulting from these experiments, are presented in Fig. 3, Fig. 4, and Fig. 5.

A. Experiment 1 (Motion Without Collision) Result

The result of this experiment is presented in Fig. 3. Based on the controller of the KUKA LWR manipulator, the actual signal of position and velocity is coinciding with the desired (commanded) signal. This means that the error is approximately zero and the effectiveness of the implemented controller. In case of there is no collision (Fig. 3), there are spikes in the actual accelerations and velocities for both joints. These spikes are from the inertial forces affected on the links of the manipulator. Joint 2 experienced larger spikes in acceleration compared to Joint 1. The measured/computed joint torque for joint 1 is higher than the torque of joint 2.

B. Experiment 2 (Collision on Link Between Joints) Result

The result of this experiment is presented in Fig. 4. As shown in Fig. 4, spikes that appeared in actual acceleration were caused by collisions, as well as by inertia and friction forces. Joint 2's acceleration remained more affected than Joint 1's due to the collision's proximity to Joint 2. There are very small spikes on the actual position and the velocity that occur from the collisions and the inertial forces applied on the links. When there are collisions on the link between the two joints (link 1), a small effect occurs in the torque of joint 2 because of the inertial force applied on the link. The measured/computed joint torque for joint 1 is higher than the torque of joint 2.

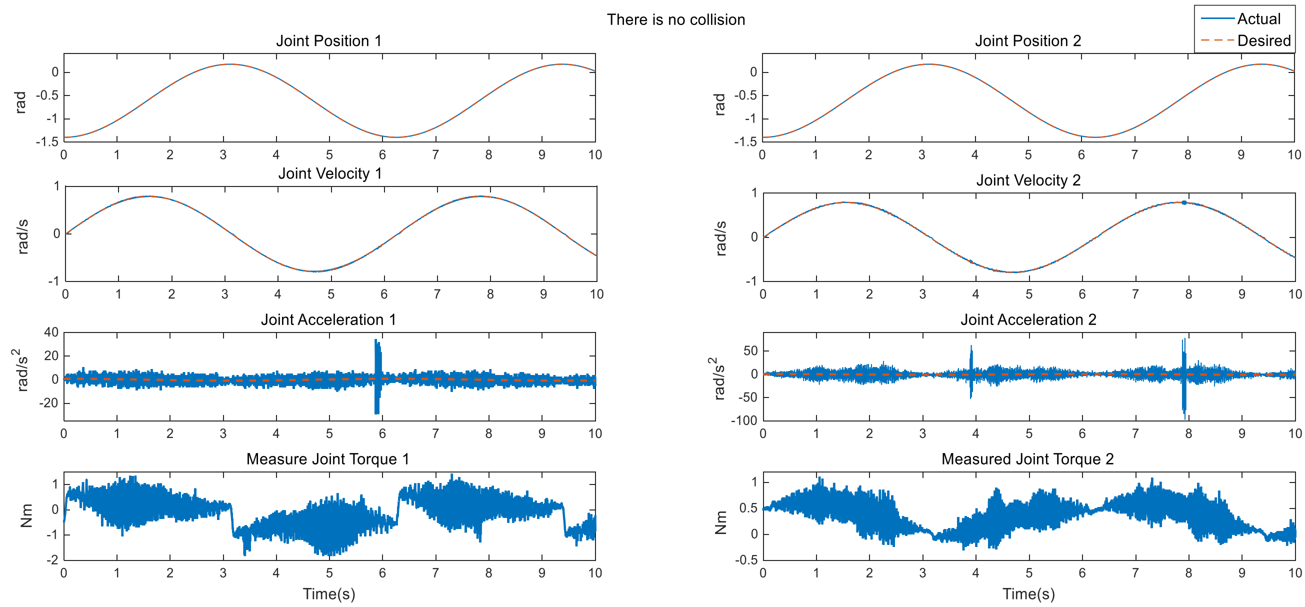
C. Experiment 3 (Collision on the End-Effector) Result

The result of this experiment is presented in Fig. 5. As shown in Fig. 5, the actual acceleration of joint 2 is always more affected than that of joint 1 when there is a collision on the end-effector (link 2). It should be noted here that the spikes in the actual acceleration are coming from collisions, inertia and friction. The actual acceleration for both joints is more affected when there is a collision on the end-effector than on the link between the two joints. There are very small spikes on the actual position and the velocity that occur from the collisions and the inertial forces applied on the links. The torque of both joints here is clearly affected by the collision. The measured/computed joint torque for joint 1 is always higher than the torque of joint 2 when there is a collision on the end-effector (link 2).

D. Key Observations from Experiment 1, 2, and 3 Results

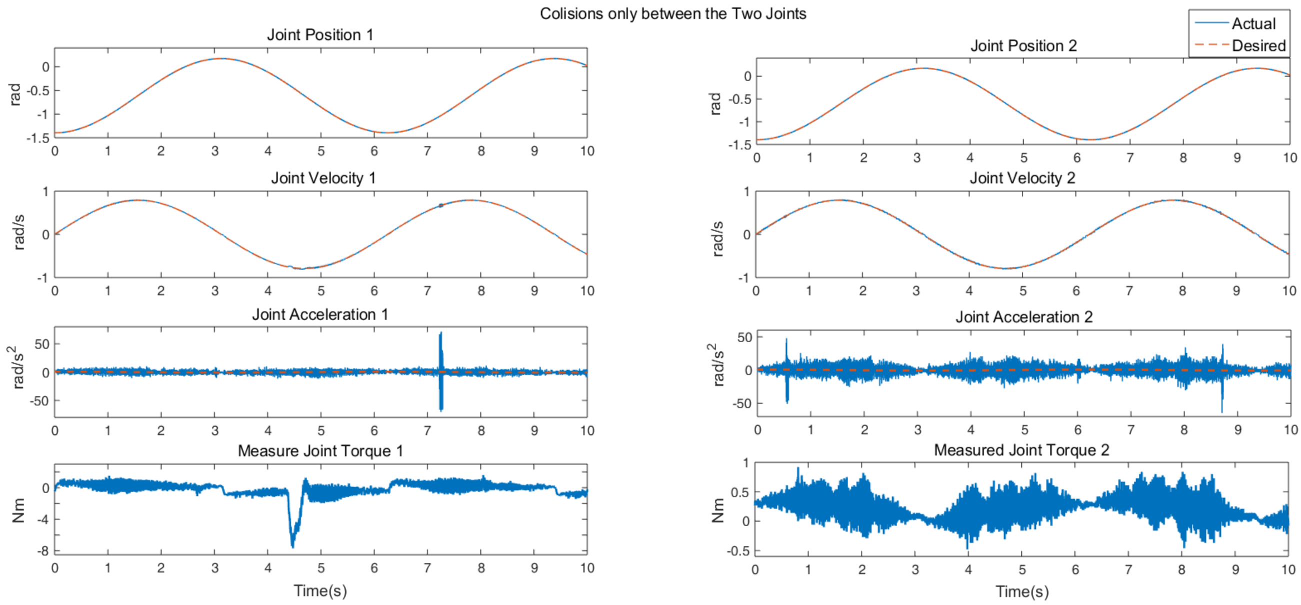
The key observation of the results from the three previous experiments are presented as follows:

- No collision scenario: Small spikes occur due to inertial forces.
- Collision on link between joints (link 1): Significant spikes in joint 1 torque, and minimal effect on joint 2 torque.
- Collision on end-effector (link 2): Elevated spikes in joint 2's dynamics due to increased speed and force transfer. The joint 1's dynamics are highly affected.



(a) Joint 1's parameters (b) Joint 2's parameters

Fig. 3. The actual and desired joints positions, velocities, accelerations and the measured joints torques when there are no collisions



(a) Joint 1's parameters (b) Joint 2's parameters

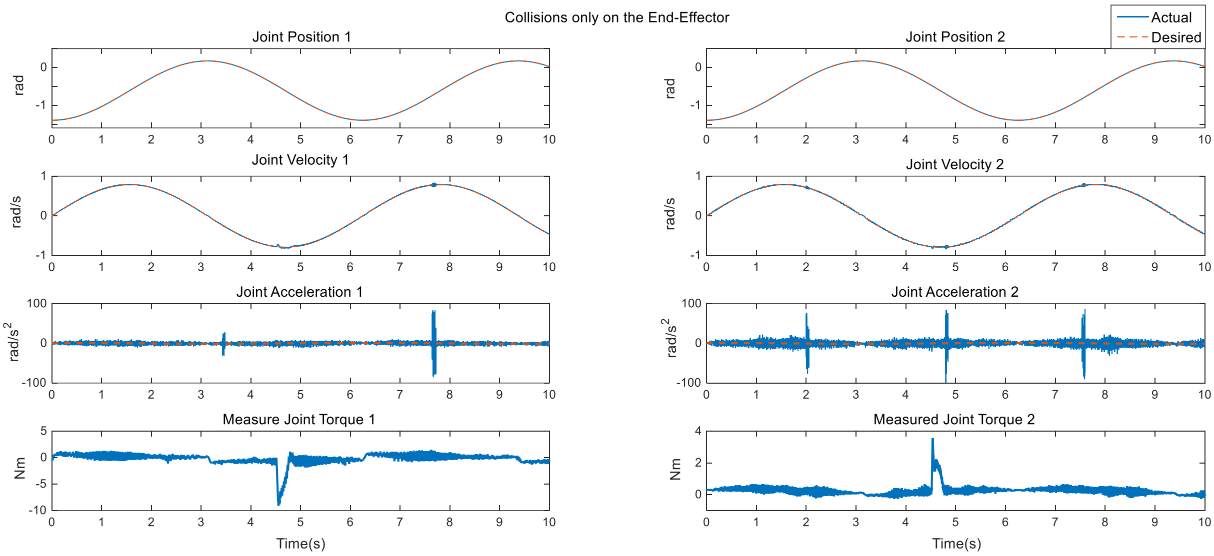
Fig. 4. The actual and desired joints positions, velocities, accelerations and the measured joints torques when there is collision between the two joints only

E. Results of Experiments 4, 5, and 6 (Different Constant Speed Motions)

New experiments are carried out to identify/investigate the measured joint torques and the external torques of the two joints considering only a collision on the link between the two joints (link 1). Three constant speeds; low (0.5rad/s), medium (1.0 rad/s), and high (1.5 rad/s) are used. With each speed, three experiments are also done, and one collision only occurs per experiment at different configuration of the two links. The different configurations where the collision occurs are when $\theta_1 = -90\ and\ \theta_2 = -90,\ \theta_1 = 90\ and\ \theta_2 = 90$, and $\theta_1 = 0\ and\ \theta_2 = 0$ whereas the range of θ_1 motion is from -90 to 90 deg and the same for θ_2. From the results shown in Fig. 6, Fig. 7, and Fig. 8, it is noted clearly that when there is a collision between the two joints a small effect on the measured joint torque of joint 2 occurs at the time when the collision occurs (small blank spot in Figures). This effect is small with the two first configurations because the two links are perpendicular to each other reducing the impact of inertial forces. The effect is high with the third configuration where the two links are in the same line so there is more effect from the inertia, or in another meaning due to increased inertial effects. Also, it should be noted that this effect becomes higher with the increase of the speed as shown in the Figures. Higher speeds amplified the torque effects across all configurations, highlighting the influence of motion velocity on collision dynamics.

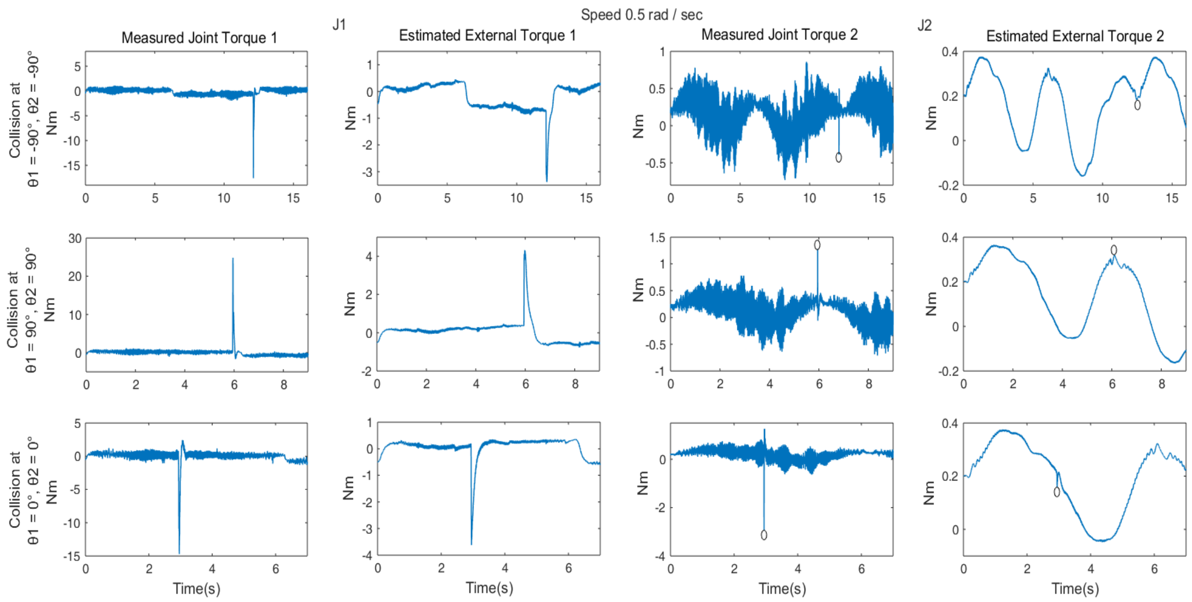
F. Recommendations from Results

The main findings and results from the all-previous experiments suggest that adaptive or collision-aware control algorithms could be designed to compensate for the inertial force-induced spikes in joint dynamics, ensuring smoother manipulator operation.



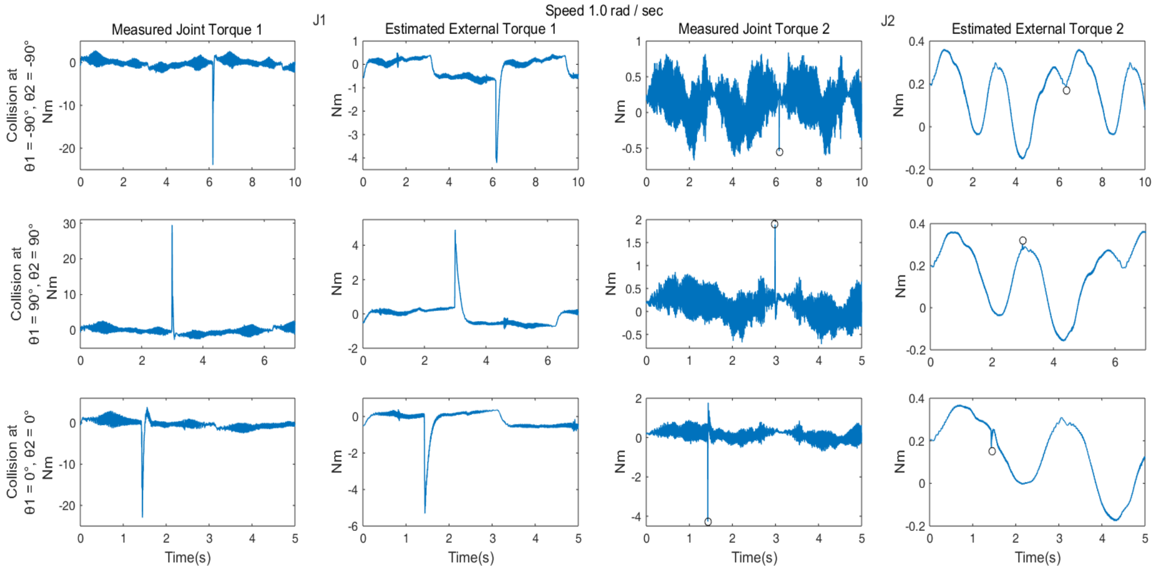
(a) Joint 1's parameters (b) Joint 2's parameters

Fig. 5. The actual and desired joints positions, velocities, accelerations and the measured joints torques when there is collision at the end-effector only



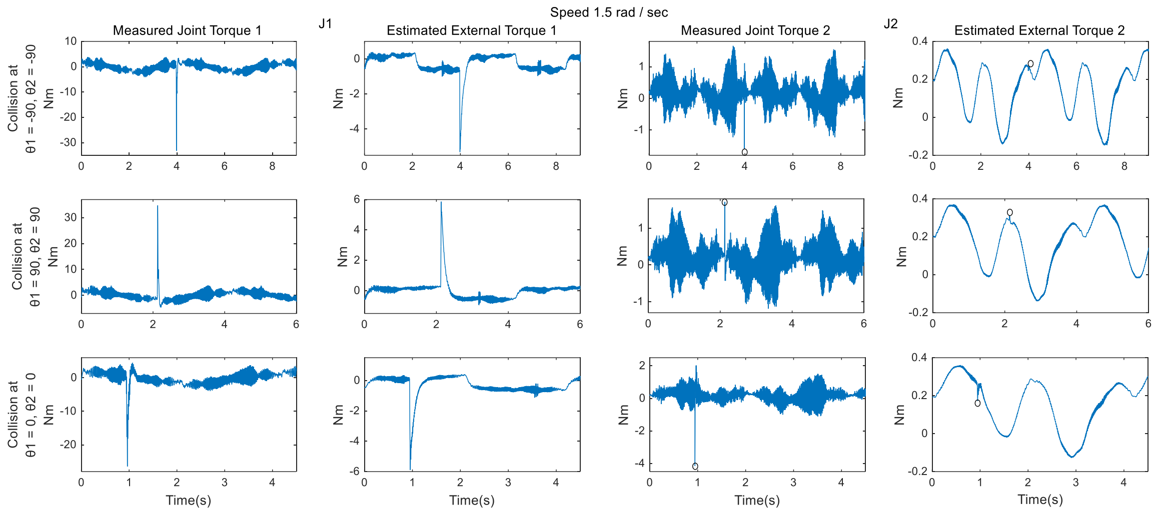
(a) Joint 1 (b) Joint 2

Fig. 6. The measured joint torques and the estimated external torques from KRC at speed 0.5 rad/s when there is only one collision between the joints at three different configurations of the two links



(a) Joint 1's parameters (b) Joint 2's parameters

Fig. 7. The measured joint torques and the estimated external torques from KRC at speed 1.0 rad/s when there is only one collision between the joints at three different configurations of the two links



(a) Joint 1 (b) Joint 2

Fig. 8. The measured joint torques and the estimated external torques from KRC at speed 1.5 rad/s when there is only one collision between the joints at three different configurations of the two links

IV. Conclusion

In this paper, the influence of the inertial and external forces on the joints' positions, velocities, accelerations, and torques of the robotic manipulator is investigated and assessed. For this purpose, a 2-DOF robotic manipulator is used, and different scenarios are investigated. These different scenarios include the application of sinusoidal joint motion of free of any collision and another motion with collision on the link between the two joints (link 1) and on the end-effector (link 2). In addition, different joint motions with constant speeds and applied collisions are carried out. The results reveal that in the absence of collisions, small spikes are observed in the actual accelerations and velocities of both joints. These spikes are coming from the inertial forces affected the links of the manipulator. In case of collision on the manipulator links, there are spikes in the joints' positions, velocities, accelerations, and torques which are coming from the collisions and the inertial forces. The measured and external joint torque for the first joint is always higher than the torque of the second joint whether there is no collision or is a collision on the end-effector (link 2) or a collision between the two joints (link 1). When there are collisions between the two joints (link 1), a small effect occurs in the torque of joint 2 because of the inertial force applied on the link. This effect is increased by the increase in the speed of the joint motion. These results underscore the importance of robust control algorithms capable of mitigating the effects of inertial forces and collisions, particularly in applications involving high-speed manipulator movements or interactions with dynamic environments.

V. Future Work

Future work will consider the following points:

- Application of the same approach using 7-DOF manipulator by studying the effect of the external force on the 7-joints parameters.

- The estimation of the external force using advanced algorithms can be implemented.
- Adaptive control strategies will be explored to enhance robustness against unforeseen external disturbances and extend the analysis to higher-DOF systems.
- Investigation of the influence of varying payloads, more degrees of freedom, and different collision surfaces to generalize the findings to more complex robotic systems.

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