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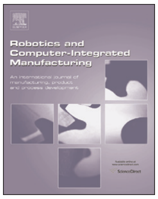

Modeling and simulation for fatigue life analysis of robots with flexible joints under percussive impact forces

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ABSTRACT

This paper presents a method for modeling and analyzing the fatigue life of robots with flexible joints, with a particular focus on applications under percussive impact forces. This development is motivated by growing interests in robotic automation for operations with percussive impact tools. The most important characteristic of percussive operations is the repetitive impacts generated by the tool, such as a percussive rivet gun. After modeling of a flexible joint robot, a forced vibration solution is provided by including the impact forces generated by the percussive gun, projecting them onto the robot joint space and treating them in terms of the Fourier transform. As a result, the joint angular displacements can be solved using a standard vibration method. Then the joint stresses can be determined through Hooke's law. To consider the stress variations caused by the robot operating at different poses using different rivets, a multiple-loading fatigue model is applied from which an equation is derived to determine the total number of the rivets that can be riveted before robot's fatigue failure. Based on simulation using our model, the following observations are received. First, the joint torsional stresses vary with robot's position and orientation. Second, no joint will always experience the maximum stress and the joint stress dominancy also varies with robot's position and orientation. Third, at a given riveting point, the rivet gun direction considerately affects the joint stresses. Fourth, the fatigue life of each joint is different; therefore robot's fatigue life should be evaluated based on the shortest joint fatigue life.

1. Introduction

In the past few decades, robots have been playing a significant role in industrial automation to provide high productivity, adaptability, quality, and low cost. They have been used in a wide range of fields, such as machining, assembly, packaging, and material handling [1]. A robotic automation system usually includes a robot and a tooling system. A tooling system is composed of tools, such as grippers and cutting tools, along with a tool mount that is attached to the robot's end-effector. Though most industrial robots are designed for general applications, tooling systems are usually customized according to specific tasks. In this paper, we focus on the automation tasks that require percussive tools. These tools have been widely used as hammers, drills, chippers, road breakers, and rivet guns in many industries, such as the civil construction and aerospace manufacturing [2,3]. For some industrial applications, manual percussive operations can be tedious, repetitious, costly, and prone to error, and can cause health and ergonomic problems related to human joint fatigue [4,5]. Therefore, there have been increasing interests in the automation for manual operations using percussive tools, especially in the aerospace manufacturing industry [6–8]. This automation becomes necessary for new unmanned tasks using percussive tools. For instance, percussive drilling tools have recently been proposed for unmanned Mars exploration [9].

The most important characteristic of percussive operations is the repetitive impacts generated by the tool. Due to this highly impact feature, the success of their robotic automation demands specific research on these applications. Limited works have been published in literature on the robotic automation of percussive operations. Glass et al. [9] designed, tested, and analyzed the performance of a new percussive drilling tool for unmanned Mars exploration. Jayaweera and Webb [10] presented a robotic riveting assembly system for typical aircraft panels and investigated the positioning accuracy of the robot with a laser metrology device. Though not explicitly mentioned, their robotic system could be adopted to percussive riveting. These works are mainly focused on the design, integration, and test of automatic system for percussive operations. The performance of the percussive tool and the robot are demonstrated respectively, but little discussion has been given on the dynamics mechanism of percussive impacts.

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Nomenclature

Symbol	Description
l	Link length
m_i	Mass of the i^{th} link
$\boldsymbol{n}$	Unit vector representing the force direction
$\boldsymbol{n_d}$	Unit vector used in the decoupled system
n_{i}	Number of cycles at working stress
$\mathbf{q}_0$	Vector of joint coordinates at an equilibrium configuration
$\Delta\mathbf{q}$	Vector of joint deflections
$\Delta\dot{\mathbf{q}}$	Vector of joint deflection rates
$\Delta\mathbf{q}_0$	Vecror of transient response of joint vibration displacements
$\Delta\mathbf{q}_{ss}$	Vector of steady-state response of joint vibration displacements
r	Radius of the joint shaft
Δs	Arc length of the joint shaft
$\boldsymbol{v}$	Vector of the velocity of the end-effector
$\mathbf{w}$	Vector of the wrench acting on the end-effector
$\mathbf{D}$	Diagonal matrix of ω_i^2
$\boldsymbol{F}_E$	Vector of the external forces acting on the end-effector
$\boldsymbol{F}(\mathrm{t})$	Vector of periodic pulsive forces
G	Shear modulus of the joint shaft
J	
$\mathbf{J}$	$6 \times n$ Jacobian matrix
K	$n \times n$ generalized stiffness matrix
$\boldsymbol{K_d}$	$n \times n$ decoupled stiffness matrix
M	$n \times n$ generalized mass matrix
$\boldsymbol{M_d}$	$n \times n$ decoupled mass matrix
$\boldsymbol{M}_E$	Vector of the external moments acting at the end-effector
N_{i}	Number of cycles to failure
$\mathbf{S}$	Matrix of the time-independent normal mode shape
T_e	Elastic energy
T_k	Kinetic energy
$\boldsymbol{\gamma}$	Shear strain
$\boldsymbol{\eta}$	Vector of the time-dependent generalized coordinates
η_i	The ith element of vector $\boldsymbol{\eta}$
θ	Joint angle
ς	Damping ratio
$\boldsymbol{\tau}$	Vectror of torsional stresses
$\boldsymbol{\omega}$	Vector of the angular velocity of the end-effector
$\omega_{\boldsymbol{i}}$	The ith natural frequency of the system

The dynamics of percussive operations involves the impacts generated by the tool and the interaction between the tool and the part. Kadam [11] and Bloxsom [12] investigated the modeling of pneumatic percussive hammers. They demonstrated how the repetitive impacts were produced through simulation. Quan et al. [13] presented and implemented the dynamic simulation of the percussive driving mechanism for a rotary-percussive drilling tool. The impact energy produced by the percussive tool was modeled by a spring-mass model. Johnson et al. [14] proposed a three degrees-of-freedom (DOF) analytical dynamics model to simulate percussive riveting and to investigate the dynamic interaction between the operator, the gun, and the part. Li et al. [15] studied how the inertia of the percussive rivet gun could affect the acceleration, natural frequencies, and energy consumption of the robot. The above researches have provided some insight into the complex dynamics of percussive operations, indicating the importance of studying the dynamics of percussive operations for their robotic automation.

A most significant issue for percussive operations is the structural fatigue due to the repetitive impacts, which has been addressed for manual operations [4,5]. The human health risks can be eliminated by robotic automation, but robots are flexible structures and have limited life expectancy. The life limit of a robot relates to the performance of its mechanical and electrical components. The life expectancy of an industrial robot can largely vary from five to twenty years, depending on the operating conditions and care of service [16]. For percussive operations, because of the repetitive impacts, the torsional stress in robot joints can vary greatly in a relatively short time. It has been demonstrated that varying torsional stress can lead to stress fatigue to machine shafts [17]. Extensive research on the dynamics and control of flexible robots can be found in literature. These works cover various topics including stiffness mapping, dynamic modeling, inverse dynamics, vibration control, and parameter estimation. The readers are referred to three review articles [18–20] for more detail on the works on the dynamics and control of flexible robots. However, to the knowledge of the authors, only a few studies have been published on the fatigue analysis of flexible robots. Du, Yu, and Su [21] analyzed the dynamic stress of linkages of a 3-RRR parallel robot under bending and then used the stress results to calculate the fatigue cycle. Miclosina and Campian [22] investigated the fatigue of a parallel robot, where the stress of the flexible linkages was calculated by Finite Element Analysis (FEA) in SolidWorks. In both works, the robot was considered to performance simple point-to-point motion. Thus, these works cannot represent the percussive operations with highly impact dynamics.

To estimate the cost, efficiency, and life limit of a robotic system for percussive operations, the fatigue life of the robot under repetitive impact forces must be predicted. This paper aims to overcome this problem.

2. System description and problem statement

A robotic riveting system has been developed at Shanghai University [23]. As shown in Fig. 1, this system includes four robots. A Fanuc M-20iA robot is used to hold and drive a percussive rivet gun. Two Kawasaki JS010G-A robots are used to form a flexible jig to hold a piece of sheet metal, and an ABB IRB 2600 robot is used to hold a bucking bar for support during riveting. As shown in Fig. 2, in riveting a hole has to be drilled first, then a rivet is inserted into the hole and deformed by force. For complete sheet metal riveting, the Fanuc robot will move point-to-point along a pre-planned path and the ABB robot will follow the same path in

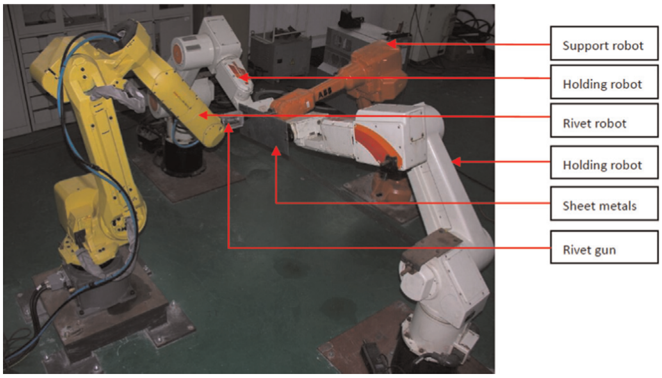

Fig. 1. A robotic percussive riveting system.

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