Faculty of Engineering
University of Kragujevac

Ministry of Science, Technological Development and Innovation

11th International Congress
Motor Vehicles & Motors 2026

ECOLOGY - VEHICLE AND ROAD SAFETY - EFFICIENCY

Proceedings



University of Kragujevac

Department for Motor Vehicles and Motors

International Journal for Vehicle Mechanics, Engines and Transportation Systems

October 8th - 9th, 2026
Kragujevac, Serbia

11th International Congress
Motor Vehicles & Motors 2026

ECOLOGY - VEHICLE AND ROAD SAFETY - EFFICIENCY

BOOK OF PROCEEDINGS

October 8th - 9th, 2026
Kragujevac, Serbia

Publisher: The Faculty of Engineering of the University of Kragujevac
Serbia, 34000 Kragujevac, Sestre Janjić 6

For Publisher: Prof. Slobodan Savić, Ph.D.
Dean of the Faculty of Engineering

Editors: Prof. Danijela Miloradović, Ph.D.
Assist. prof. Nadica Stojanović, Ph.D.
The Faculty of Engineering of the University of Kragujevac

Technical preparation: Asisst. Prof. Nadica Stojanović, Ph.D.

Cover: Nemanja Lazarević

USB edition: Faculty of Engineering, University of Kragujevac, Kragujevac

ISBN: 978-86-6335-132-5

Year of publication: 2026.

Published on USB by: InterPrint
Aleksinačka St. nn, 34000 Kragujevac, Serbia

Number of copies: 100

CIP - Каталогизација у публикацији Народна библиотека Србије, Београд

629.3(082)(0.034.2)
621.43(082)(0.034.2)

INTERNATIONAL Congress Motor Vehicles & Motors (11 ; 2026 ; Kragujevac)
Ecology - Vehicle and Road Safety - Efficiency [Elektronski izvor] : proceedings / 11th international congress Motor vehicles & motors 2026, October 8th - 9th, 2026 Kragujevac, Serbia ; [editors Danijela Miloradović, Nadica Stojanović]. - Kragujevac : University, Faculty of Engineering, 2026 (Kragujevac : InterPrint). - 1 USB fleš memorija ; 1 x 2 x 6 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa nasl. strane dokumenta. - Tiraž 100. - Bibliografija uz svaki rad.

ISBN 978-86-6335-132-5

a) Моторна возила -- Зборници b) Моторни са унутрашњим сагоревањем -- Зборници

COBISS.SR-ID 201905929

Publishing of this USB Book of proceedings was supported by
Ministry of Science, Technological Development and Innovation of the Republic of Serbia

Copyright © 2026 Faculty of Engineering, University of Kragujevac

This book is published online with Open Access and distributed under the terms of the Creative Commons Attribution License 4.0 (CC BY 4.0).

SCIENTIFIC BOARD

President

Prof. Danijela Miloradović, Ph.D., UniKg, FE, Serbia

Secretaries

Assist. Prof., Slavica Mačužić Saveljić, Ph.D., UniKg, FE, Serbia
Assist. Prof., Saša Milojević, Ph.D., UniKg, FE, Serbia

Members

Prof. Oday Ibraheem Abdulah, ANUni, CoE, Baghdad, Iraq
Assist. Prof. Ali Belhocine, UniMSM, FST, Mascara, Algeria
Emeritus Prof. Giovanni Belingardi, Ph.D., PoliTo, Turin, Italy
Prof. Murat Ciniviz, Ph.D., SelUni, FT, Konya, Turkey
Prof. Adrian Clenci Ph.D., UniPolBU, Bucharest, Romania
Prof. Bruno Dalla Chiara, Ph.D., PoliTo, Turin, Italy
Assoc. Prof. Aleksandar Davinić, Ph.D., UniKG, FE, Kragujevac, Serbia
Prof. Miroslav Demić, Ph.D., UniKG, FE, Kragujevac, Serbia
Prof. Jovan Dorić Ph.D., UniNS, FTS, Novi Sad, Serbia
Prof. Mohamed Ali Emam, Ph.D., HUni, FE, Cairo, Egypt
Prof. Jasna Glišović, Ph.D., UniKG, FE, Kragujevac, Serbia
Prof. Valentina Golubović Bugarski, Ph.D., UniBL, FME, Banja Luka, RS, Bosnia and Herzegovina
Assoc. Prof. Ivan Grujć, Ph.D., UniKG, FE, Kragujevac, Serbia
Prof. Rosen Hristov, Ph.D., TU Varna, Varna, Bulgaria
Prof. Aleksandra Janković, Ph.D., UniKG, FE, Kragujevac, Serbia
Assoc. Prof. Aleksandar Jovanović, Ph.D., UniKG, FE, Kragujevac, Serbia
Prof. Emrullah Hakan Kaleli, Ph.D., YTU, Istanbul, Turkey
Prof. Janez Kopač, Ph.D., UniLJ, FME, Ljubljana, Slovenia
Prof. Jovanka Lukić, Ph.D., UniKG, FE, Kragujevac, Serbia
Assist. Prof. Slavica Mačužić Saveljić, Ph.D., UniKG, FE, Kragujevac, Serbia
Assist. Prof. Saša Milojević, Ph.D., UniKG, FE, Kragujevac, Serbia
Assist. Prof. Slobodan Mišanović, Ph.D., CPTC Belgrade, Belgrade, Serbia
Prof. Alexander Novikov, Ph.D., OSUni, Orel, Russian Federation
Prof. Sreten Perić, Ph.D., UniD, MA, Belgrade, Serbia
Prof. Radivoje Pešić, Ph.D., UniKG, FE, Kragujevac Serbia
Prof. Snezana Petković, Ph.D., UniBL, FME, Banja Luka, RS, Bosnia and Herzegovina
Prof. Ralph Puetz, Ph.D., LUniAS, Landshut, Germany
Prof. Dragan Ružić, Ph.D., UniNS, FTS, Novi Sad, Serbia
Prof. Mikhail Shatrov, Ph.D., MADI, Moscow, Russian Federation
Assoc. Prof. Aleksandar Stevanović, Ph.D., UniPitt, Pittsburgh, USA
Assist. Prof. Nadica Stojanović, Ph.D., UniKG, FE, Kragujevac, Serbia
Assoc. Prof. Boris Stojić, Ph.D., UniNS, FTS, Novi Sad, Serbia
Prof. Radoje Vujadinović, Ph.D., UniMN, FME, Podgorica, Montenegro
Assoc. Prof. Predrag Živanović, Ph.D., UniBG, FTTE, Belgrade, Serbia

ORGANIZATIONAL BOARD

President

Asst. Prof., Nadica Stojanović, Ph.D., UniKg, FE, Serbia

Secretaries

Assist. Prof., Slavica Mačužić Saveljić, Ph.D., UniKg, FE, Serbia
Assist. Prof., Saša Milojević, Ph.D., UniKg, FE, Serbia

Members:

Prof. dr Jovanka Lukić, UniKg, FE, Kragujevac, Serbia
Prof. dr Jasna Glišović, UniKg, FE, Kragujevac, Serbia
Assoc. Prof. dr Aleksandar Davinić, UniKg, FE, Kragujevac, Serbia
Assoc. prof. dr Aleksandar Jovanović, UniKg, FE, Kragujevac, Serbia
Assoc. prof. dr Ivan Grujić, UniKg, FE, Kragujevac, Serbia

MVM2026 CONGRESS ORGANIZERS

Faculty of Engineering of the University of Kragujevac
Department for Motor Vehicles and Motors, FE Kragujevac
International Journal “Mobility & Vehicle Mechanics”

MVM2026 CONGRESS PATRONS

Ministry of Science, Technological Development and Innovation of the Republic of Serbia
Faculty of Engineering of the University of Kragujevac

MVM2026 CONGRESS REVIEWERS

Prof. dr Oday Ibraheem Abdulah, UniBAG, CoE, Baghdad, Iraq
Assist. Prof. dr Ali Belhocine, UniMSM, FST, Mascara, Algeria
Emeritus Prof. dr Giovanni Belingardi, PoliTo, Turin, Italy
Assoc. Prof. dr Aleksandar Davinić, UniKG, FE, Kragujevac, Serbia
Prof. dr Miroslav Demić, UniKG, FE, Kragujevac, Serbia
Prof. dr Jovan Dorić, UniNS, FTS, Novi Sad, Serbia
Prof. dr Jasna Glišović, UniKG, FE, Kragujevac, Serbia
Prof. dr Valentina Golubović Bugarski, UniBL, FME, Banja Luka, RS, Bosnia & Herzegovina
Assoc. Prof. dr Ivan Grujić, UniKG, FE, Kragujevac, Serbia
Prof. dr Rosen Hristov, TU Varna, Varna, Bulgaria
Assoc. Prof. dr Aleksandar Jovanović, UniKG, FE, Kragujevac, Serbia
Prof. dr Janez Kopač, UniLJ, FME, Ljubljana, Slovenia
Prof. dr Jovanka Lukić, UniKG, FE, Kragujevac, Serbia
Assist. Prof. dr Slavica Mačužić Saveljić, UniKG, FE, Kragujevac, Serbia
Assist. Prof. dr Saša Milojević, UniKG, FE, Kragujevac, Serbia
Prof. dr Danijela Miloradović, UniKG, FE, Kragujevac, Serbia
Assist. Prof. dr Slobodan Mišanović, CPTC Belgrade, Belgrade, Serbia
Prof. dr Radivoje Pešić, UniKG, FE, Kragujevac Serbia
Prof. dr Snezana Petković, UniBL, FME, Banja Luka, RS, Bosnia & Herzegovina
Prof. dr Dragan Ružić, UniNS, FTS, Novi Sad, Serbia
Assoc. Prof. dr Aleksandar Stevanović, UniPitt, Pittsburgh, USA
Assist. Prof. dr Nadica Stojanović, UniKG, FE, Kragujevac, Serbia
Assoc. Prof. dr Boris Stojić, UniNS, FTS, Novi Sad, Serbia

FOREWORD

For 47 years, a traditional international gathering - originally known as a Symposium and, since 2006, as the "Motor Vehicles and Motors" Congress - has been held biennially at the Faculty of Engineering (formerly the Faculty of Mechanical Engineering) of the University of Kragujevac. This year, the 11th International Congress "Motor Vehicles and Motors" took place in Kragujevac on October 8th–9th, 2026, under the traditional motto: "Ecology – Vehicle and Road Safety – Efficiency".

A large number of authors from both the country and abroad responded to the organizers' invitation, resulting in numerous high-quality submissions across the event's core areas: "Power Train Technology," "Vehicle Design and Manufacturing," "Vehicle Dynamics and Intelligent Control Systems," "Driver/Vehicle Interface, Information Systems, and Assistance Systems," and "Transport Challenges in Emerging Economies." Additionally, two topics were officially introduced for the first time: "Artificial Intelligence in Automotive Technology" and "Autonomous Vehicles".

A total of 63 papers were accepted for presentation following a rigorous peer-review process. The presentations were organized into sessions, including a newly introduced poster session dedicated to students and young researchers.

The Congress organizers extend their special gratitude to the distinguished scientists in the fields of motor vehicles and transportation who agreed to deliver three inspiring introductory lectures addressing the heart of contemporary issues in the sector: prof. dr Ralph Putz (Landshut University of Applied Sciences, Germany), prof. dr Aleksandar Stevanović (University of Pittsburgh, USA), and prof. dr. Isak Karabegović (Academy of Sciences and Arts of Bosnia and Herzegovina, Bosnia and Herzegovina).

We extend our sincere gratitude to the esteemed members of the Congress Scientific Committee—who also served as reviewers for the papers submitted for presentation—for their significant contribution to the overall quality of the accepted papers.

The organization of the Congress was once again supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, the Faculty of Engineering of the University of Kragujevac, and the International journal “Mobility & Vehicle Mechanics” and we sincerely thank them for their support.

Scientific Board and Organizational Board of MVM2026 Congress

PREDGOVOR

Već 47 godina, svake druge godine, na Fakultetu inženjerskih nauka (nekada Mašinskom fakultetu) Univerziteta u Kragujevcu održava se tradicionalan međunarodni skup, nekada nazivan Simpozijum, a od 2006. godine - Kongres „Motorna vozila i motori“. Ovogodišnji, 11. Međunarodni kongres „Motorna vozila i motori“ održan je u Kragujevcu od 8. do 9. oktobra 2026. godine, uz tradicionalni moto „Ekologija – Vozilo i bezbednost na putu – Efikasnost“.

Na poziv organizatora odazvao se veliki broj autora iz zemlje i inostranstva, što je donelo veliki broj prijavljenih kvalitetnih radova iz glavnih oblasti skupa: „Tehnologija pogonskog sistema“, „Dizajn i proizvodnja vozila“, „Dinamika vozila i inteligentni upravljački sistemi“, „Interfejs vozač/vozilo, informacioni sistemi i sistemi za pomoć“, „Transportni izazovi ekonomija u usponu“, uz prvi put zvanično promovisane teme – „Veštačka inteligencija u automobilskoj tehnologiji“ i „Autonomna vozila“.

Ukupan broj od 63 radova je prihvaćen za prezentaciju posle rigoroznog procesa recenziranja. Rad je organizovan po sekcijama, uz prvi put promovisanu poster sekciju namenjenu za studente i mlade istraživače.

Organizatori Kongresa su posebno zahvalni istaknutim naučnicima iz oblasti motornih vozila i saobraćaja koji su pristali da održe tri inspirativna uvodna predavanja koja zadiru u srž savremenih pitanja vezana za vozila i saobraćaj, a to su: prof. dr Ralph Putz (Landshut University of Applied Sciences, Nemačka), prof. dr Aleksandar Stevanović (University of Pittsburgh, SAD) i prof. dr Isak Karabegović (Akademija nauka i umjetnosti Bosne i Hercegovine, Bosna i Hercegovina).

Veliku zahvalnost dugujemo našim dragim članovima Naučnog odbora Kongresa, ujedno i recenzentima radova prijavljenih za prezentaciju na Kongresu, koji su mnogo doprineli ukupnom kvalitetu konačno prihvaćenih radova.

Organizaciju Kongresa i ovog puta su podržali: Ministarstvo nauke, tehnološkog razvoja i inovacija Republike Srbije, Fakultet inženjerskih nauka Univeziteta u Kragujevcu i Međunarodni časopis „Mobility & Vehicle Mechanics“, na čemu im se iskreno zahvaljujemo.

Naučni odbor i Organizacioni odbor Kongresa MVM2026

CONTENT

INTRODUCTORY LECTURES

MVM2026-IL1	Ralph Pütz	OPERATING COSTS OF PUBLIC TRANSPORT BUSES WITH DIFFERENT PROPULSION SYSTEMS AND VARIOUS TYPES OF RENEWABLE ENERGY OVER TIME – WHERE IS THE JOURNEY HEADING?	3
MVM2026-IL3	Isak Karabegović	COLLABORATIVE ROBOTICS AND ARTIFICIAL INTELLIGENCE IN THE AUTOMOTIVE INDUSTRY: SMART ASSEMBLY AND AUTOMATED QUALITY CONTROL	13

SECTION A
Power Train Technology

MVM2026-003	Ivan Grujic Aleksandar Davinic Zeljko Djuric Jovan Doric Milan Eremija Attila Kiss Sunny Narayan	THE INVESTIGATION OF THE COMBUSTION PROCESS OF THE BLEND OF THE CONVENTIONAL DIESEL FUEL AND BIODIESEL MADE FROM THE WASTE GRAPE SEEDS	35
MVM2026-008	Željko Đurić Ivan Grujić Nadica Stojanović Snežana Petković Jelena Adžić Milan Eremija	EXPERIMENTAL INVESTIGATION OF THE COMBUSTION PROCESS AND EFFICIENCY OF A DIESEL ENGINE IN THE CASE OF BIODIESEL FUEL APPLICATION	41
MVM2026-011	Milan Eremija Ivan Grujić Danijela Miloradović Željko Đurić Svetko Milutinović Nadica Stojanović	EXPERIMENTAL ANALYSIS OF EXHAUST GAS TEMPERATURE DURING THE USE OF BIODIESEL FUEL	53
MVM2026-013	Krasimir Markov Hristo Stanchev	INVESTIGATION OF THE FUEL CONSUMPTION AND EMISSIONS OF A DIESEL ENGINE RUNNING ON DIESEL WITH AN ADDITIVE	61
MVM2026-015	Milan Eremija Zoran Ristikić Svetko Milutinović Mesud Ajanović	EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF TIRE PRESSURE ON THE ROLLING RESISTANCE COEFFICIENT OF COMMERCIAL VEHICLES	67
MVM2026-025	Marko Lučić Mirjana Grdinić-Rakonjac Radoje Vujadinović Vladimir Pajković Ivan Grujić	ENERGY USE IN MONTENEGRO'S ROAD TRANSPORT SECTOR: TRENDS, FUEL STRUCTURE AND DEPENDENCE ON PETROLEUM-BASED FUELS	77

MVM2026-030	Vladimir Kočović Živana Jovanović Pešić Miloš Pešić Jelena Đusić Dragan Džunić	TRIBOLOGICAL PERFORMANCE OF BRASS SURFACES LUBRICATED WITH NEW AND USED ENGINE OILS	85
MVM2026-034	Mihailo Đuković Saša Milojević Slobodan Savić Blaža Stojanović Horia Abaitancei	APPLICATION OF A RADIAL HYDRAULIC MOTOR IN ALTERNATIVE VEHICLE DRIVE SYSTEMS	91
MVM2026-036	Marko Kitanović Slobodan Popović Nenad Miljić Predrag Mrđa	EFFECTIVE MIXTURE COMPOSITION IN THE ANGULAR DOMAIN IN SUPERCHARGED DISI ENGINE WITH MULTIPLE INJECTIONS	111
MVM2026-037	Petar Markov Radivoje Pušara Dragan Peruničić	A SINGLE-RANGE POLYNOMIAL MODEL FOR TEMPERATURE-DEPENDENT MIXTURE PROPERTIES IN COMBUSTION ENGINES WITH VARIABLE EGR RATES	125
MVM2026-038	Dragan Peruničić Petar Markov Radivoje Pušara	MODELING OF SPECIFIC HEAT RATIO FOR DISI ENGINES WITH COMPLEX MIXTURE FORMATION AND HIGH EGR RATES	139
MVM2026-041	Predrag Mrđa Slobodan Popović Nenad Miljić Marko Kitanović	EXPERIMENTAL AND CFD-BASED INVESTIGATION OF VAPOUR POCKET FORMATION IN AN INTERNAL COMBUSTION ENGINE COOLING SYSTEM	155
MVM2026-042	Nenad Miljić Predrag Mrđa Slobodan J. Popović	QUANTIFYING IMEP EVALUATION ERROR INDUCED BY PIEZOELECTRIC PRESSURE SENSOR AGEING IN INTERNAL COMBUSTION ENGINE INDICATION	165
MVM2026-051	Saša Milojević Marija Rafailović Michal Loman Branislav Šarkan Ján Vrábel Slobodan Savić	SAFETY AND OPERATIONAL CONSIDERATIONS FOR COMPOSITE HYDROGEN AND CNG STORAGE CYLINDERS IN VEHICLES	175
MVM2026-068	Mitar Mišić Stjepan Galamboš Boris Stojić Jovan Dorić Luka Sekicki	DEVELOPMENT OF AN ELECTRONIC MEASUREMENT SYSTEM FOR TURBOCHARGER WASTEGATE ACTUATOR RESPONSE-TIME TESTING	185
MVM2026-071	Mitar Mišić Stjepan Galamboš Jovan Dorić Boris Stojić Luka Sekicki	DESIGN AND IMPLEMENTATION OF A TEST BENCH FOR EVALUATING THE DYNAMICS OF PNEUMATIC WASTEGATE ACTUATORS	193

SECTION B
Vehicle Design and Manufacturing

MVM2026-006	Gordana Bogdanović Aleksandar Radaković Dragan Čukanović Petar Knežević Aleksandar Nešović	VARIATIONAL SHEAR CONTROL IN ESL–HSDT LAMINATES FOR AUTOMOTIVE STRUCTURES	203

MVM2026-007	Gordana Bogdanović Aleksandar Radaković Petar Knežević Dragan Čukanović Marko Milošević	FATIGUE ANALYSIS OF MATERIALS AND METHODS FOR CYCLE COUNTING UNDER ARBITRARY LOAD HISTORIES	211
MVM2026-009	Julija Boskovic Ivan Grujic Stefan Djuric Nadica Stojanovic Bogdan Zivkovic Milan Ivkovic Suzana Petrovic Savic	DEVELOPMENT OF AN EXPERIMENTAL FIVE-AXIS CNC SYSTEM USING STEPPER MOTORS	219
MVM2026-012	Saša Vasiljević Jasna Glišović Slobodan Vasiljević	ANALYSIS OF EXPERIMENTAL METHODOLOGIES FOR TESTING INNOVATIVE BRAKE SOLUTIONS	235
MVM2026-016	Ljubica Spasojević Zorica Djordjević Sonja Kostić Saša Jovanović	MODAL ANALYSIS OF A COMPOSITE CRANKSHAFT FOR AN INTERNAL COMBUSTION ENGINE (ICE)	245
MVM2026-017	Zvonko Petrović Suzana Petrović Savić Milica Tufegdžić Nikola Kostić Milena Petrović	MATHEMATICAL MODELING OF HYDRAULIC DRIVE FOR THE MITSUBISHI RV-2FRL INDUSTRIAL ROBOT: INFLUENCE OF MOMENT OF INERTIA ON SERVO VALVE RESPONSE TIME	253
MVM2026-022	Marko Delić Vesna Mandić Nada Ratković Nikola Komatina Dušan Arsić Nikola Kastratović	ANALYSIS OF THE INFLUENCE OF IMPORTANT FORMING PARAMETERS IN SHEET METAL STAMPING IN AUTOMOTIVE INDUSTRY USING FEA	267
MVM2026-024	Milan Simonović Dragan Adamović Đorđe Ivković Marko Simonović	ANALYSIS OF THE POSSIBILITY OF PREDICTING THE TENSILE STRENGTH OF ADVANCED STRUCTURAL STEELS USED IN THE AUTOMOTIVE INDUSTRY USING ARTIFICIAL NEURAL NETWORKS WITH DIFFERENT NUMBERS OF NEURONS IN THE HIDDEN LAYER	275
MVM2026-026	Nenad Petrović Živana Jovanović Pešić Dragan Džunić Vladimir Kočović Strahinja Milenković	CREATING CURVED MESHES BY HEAT-FORMING 3D-PRINTED PARTS	287
MVM2026-050	Danijela Tadić Jasna Glišović Nikola Komatina	COMPARATIVE ANALYSIS OF OBJECTIVE CRITERIA WEIGHTING METHODS FOR ELECTRIC VEHICLE EVALUATION	293
MVM2026-052	Dragan Čukanović Gordana Bogdanović Aleksandar Radaković Petar Knežević	APPLICATION, MODELLING AND BENDING ANALYSIS OF COMPOSITE LAMINATES IN MODERN VEHICLES	303
MVM2026-053	Mihajlo Jevtić Aleksandra Obradović Bogdan Todorović Nebojša Hristov Damir Jerković	FINITE ELEMENT ANALYSIS OF STRUCTURAL SUPPORT REACTIONS IN WHEELED MOBILE PLATFORM UNDER HIGH-INTENSITY IMPULSIVE LOADING	311

The 11th International Congress
Motor Vehicles & Motors 2026
Kragujevac, Serbia
October 8th - 9th, 2026

Motor Vehicles & Motors

MVM2026-017
https://doi.org/10.24874/CMVM2026.017
Technical paper

Zvonko Petrović[1]
Suzana Petrović Savić[2]
Milica Tufegdžić[3]
Nikola Kostić[4]
Milena Petrović[5]

MATHEMATICAL MODELING OF HYDRAULIC DRIVE FOR THE MITSUBISHI RV-2FRL INDUSTRIAL ROBOT: INFLUENCE OF MOMENT OF INERTIA ON SERVO VALVE RESPONSE TIME

ABSTRACT: This paper describes the application of alternative hydraulic drive systems to the Mitsubishi RV-2FRL industrial robot, a 6-axis manipulator with a payload of 2 kg and repeatability of ±0.02 mm. Although the robot originally utilizes AC servo motors, certain operating conditions (explosive environments, high force-to-weight ratio requirements) favour hydraulic actuation. The main contribution of this paper is a second-order mathematical model that explicitly links the robot's moment of inertia (J = 0.18 kg·m² for the J4 axis) with the servo valve time constant (tv). The model combines Newton's rotational dynamics, the hydraulic motor torque equation, first-order valve dynamics, and the oil continuity equation. The resulting transfer function yields the key relation: settling time ts. Simulation in MATLAB for varying tv (5 to 50 ms) and J (0.18 to 0.50 kg·m²) shows that to maintain the factory positioning accuracy of the RV-2FRL robot, the servo valve time constant must be below 10 ms. Valves with tv > 20 ms cause unacceptable phase lag and overshoot. It is demonstrated in this paper that hydraulic drive is theoretically feasible, but only high-performance servo valves (tv < 10 ms) satisfy the dynamic requirements of the robot, which explains why electric drives remain optimal for small precision robots.

KEYWORDS: alternative drive systems, hydraulic servo valve, moment of inertia, settling time

[1] *Zvonko Petrović, MSc, Academy of professional studies Šumadija-Department in Trstenik, Trstenik, zpetrovic@asss.edu.rs, https://orcid.org/0000-0002-4182-4095*
[2] *Suzana Petrović Savić, Assoc. Prof., Faculty of Engineering University of Kragujevac, Kragujevac, petrovic.savic@kg.ac.rs.com, https://orcid.org/0000-0002-5629-6221*
[3] *Milica Tufegdžić, PhD, Academy of professional studies Šumadija-Department in Trstenik, Trstenik, mtufegdzic@asss.edu.rs, https://orcid.org/0000-0003-3856-1498*
[4] *Nikola Kostić, PhD, Academy of professional studies Šumadija-Department in Trstenik, Trstenik, nkostic@asss.edu.rs, https://orcid.org/0009-0007-9494-5767*
[5] *Milena Petrović, MSc, Academy of professional studies Šumadija-Department in Trstenik, address, mpetrovic@asss.edu.rs, https://orcid.org/0009-0005-8443-7107*

MATEMATIČKO MODELIRANJE HIDRAULIČKOG POGONA INDUSTRIJSKOG ROBOTA MITSUBISHI RV-2FRL: UTICAJ MOMENTA INERCIJE NA VREMENSKI ODZIV SERVO-VENTILA

REZIME: U ovom radu opisana je primena alternativnih hidrauličkih pogonskih sistema na industrijskom robotu Mitsubishi RV-2FRL, manipulatoru sa 6 osa, nosivošću od 2 kg i ponovljivošću od ±0,02 mm. Iako robot originalno koristi AC servo motore, određeni radni uslovi (eksplozivne sredine, zahtevi za velikim odnosom sila-težina) favorizuju hidrauličko upravljanje. Glavni doprinos ovog rada je matematički model drugog reda koji eksplicitno povezuje moment inercije robota (J = 0,18 kg·m² za osu J4) sa vremenskom konstantom servoventila (t_v). Model kombinuje Njutnovu dinamiku rotacije, jednačinu momenta hidrauličkog motora, dinamiku ventila prvog reda i jednačinu kontinuiteta ulja. Dobijena prenosna funkcija daje ključnu relaciju: vreme smirivanja ts. Simulacijom u MATLAB-u za različite vrednosti t_v (od 5 do 50 ms) i J (od 0,18 do 0,50 kg·m²) pokazano je da za održavanje fabričke tačnosti pozicioniranja robota RV-2FRL, vremenska konstanta servoventila mora biti ispod 10 ms. Ventili sa t_v > 20 ms izazivaju neprihvatljivo kašnjenje faze i prelet. Pokazano je u radu da je hidraulički pogon teoretski izvodljiv, ali samo visokoperformasni servoventili (t_v <10 ms) zadovoljavaju dinamičke zahteve robota, što objašnjava zašto električni pogoni ostaju optimalni za male precizne robote.

KLJUČNE REČI: alternativni pogonski sistemi, hidraulički servo ventil, moment inercije, vreme smirivanja

INTRODUCTION

Industrial robots are complex mechatronic systems whose positioning accuracy and dynamic performance are strongly influenced by the characteristics of their actuation systems. Electric servo drives are predominantly used in small and medium-sized industrial robots because they provide high positioning accuracy, rapid response, and relatively straightforward control. However, hydraulic actuation may represent a suitable alternative under specific operating conditions, particularly when high force or torque capacity, a favourable power-to-weight ratio, or operation in specially configured hazardous environments is required (Merritt, 1967; Watton, 1989).

The Mitsubishi RV-2FRL, considered in this study, is a six-axis vertically articulated industrial robot originally actuated by AC servo motors. Owing to its compact structure, low payload, and high repeatability, it represents a demanding reference platform for assessing whether an alternative hydraulic drive can satisfy the dynamic requirements of a small precision robot. In this study, the J4 axis is selected for analysis, and its moment of inertia is incorporated into the mathematical model of the proposed hydrostatic servo drive.

A hydrostatic servo system typically comprises a servo valve that regulates the hydraulic fluid flow, a hydraulic actuator in the form of a motor or cylinder, and the associated mechanical load (Jelali & Kroll, 2003). The mathematical modelling of such systems is based on the coupled equations governing fluid-flow continuity, the force or torque equilibrium of the mechanical components, and servo-valve dynamics (Blackburn et al., 1960; Nichols & Reistad, 1999). The dynamic response of the system is primarily determined by the moment of inertia of the rotating components (J); the viscous damping coefficient (B); the hydraulic motor displacement (Dm); the effective bulk modulus of the hydraulic fluid (βe); the total fluid volume between the servo valve and the motor (vt); the servo-valve gain (Kv); and the servo-valve time constant (tv) (Merritt, 1967; Watton, 1989; Jelali & Kroll, 2003).

The theoretical foundations of hydraulic control and servo systems were established in the classical works of J.F. Blackburn et al. (1960) and Merritt (1967), which provided systematic descriptions of hydraulic components, flow–pressure relationships, actuator dynamics, and system response. J. Watton (1989) subsequently integrated these principles with mathematical modelling and computer-based simulation techniques. A more comprehensive treatment of the modelling, identification, and control of hydraulic servo systems was later presented by M. Jelali and A. Kroll (2003). These fundamental studies provide the theoretical basis for deriving models that couple servo-valve dynamics, hydraulic actuator behaviour, fluid compressibility, and mechanical-load dynamics.

Accordingly, the aim of this study is to develop a transfer-function-based mathematical model for evaluating the feasibility of hydrostatic actuation of the J4 axis of the Mitsubishi RV-2FRL robot. The model combines Newton's equation of rotational motion, the hydraulic motor torque equation, a first-order representation of the servo-valve dynamics, and the hydraulic fluid continuity equation. The resulting second-order transfer function explicitly relates the moment of inertia of the robot axis to the servo-valve time constant and enables their influence on the transient response of the system to be examined.

A comparative parametric analysis is performed in MATLAB for servo-valve time constants ranging from 5 to 50 ms and moments of inertia ranging from 0.18 to 0.50 kg·m². The dynamic behaviour of the system is evaluated using unit-step responses, with particular emphasis on settling time and overshoot. The analysis is intended to determine the range of servo-valve time constants for which the proposed hydraulic drive can satisfy the dynamic-response requirements associated with the J4 axis and to identify the limitations of hydraulic actuation when applied to small, high-precision industrial robots. MATLAB Control System Toolbox is used for model implementation and response analysis.

MATERIALS AND METHODS

Mitsubishi RV-2FRL Industrial Robot

The Mitsubishi RV-2FRL is a vertically articulated industrial robot manufactured by Mitsubishi Electric and belongs to the MELFA FR series. It is a stationary six-axis manipulator designed for high-speed and high-precision handling and assembly operations. The robot can be installed on the floor or ceiling, while wall-mounted installation is available as a customised configuration with a restricted operating range of the J1 axis (Mitsubishi Electric, 2020). The Mitsubishi RV-2FRL robotic system, including the manipulator and the associated CR800 controller (Figure 1).

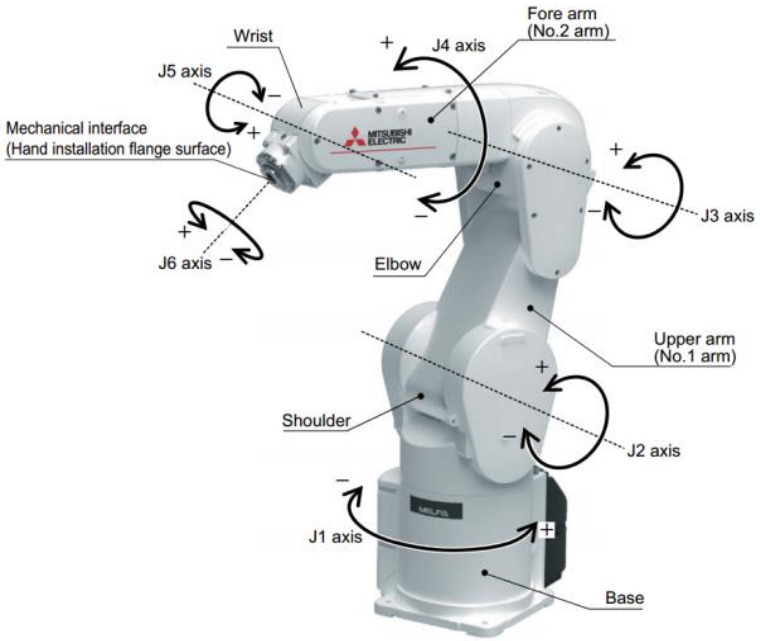


Figure 1 Mitsubishi RV-2FRL robotic system (Mitsubishi Electric, 2020)

The compact structure of the RV-2FRL, combined with its maximum reach of 649 mm and position repeatability of ±0.02 mm, makes it suitable for manipulation tasks requiring high precision within a relatively small workspace. The robot is originally actuated by AC servo motors, while the angular positions of its joints are measured using absolute encoders. Its principal technical characteristics are summarised in Table 1.

Table 1 Principal technical characteristics of the Mitsubishi RV-2FRL robot

Characteristic	**Specification**
Manufacturer	Mitsubishi Electric
Robot series	MELFA FR
Robot type	Vertically articulated industrial robot
Number of degrees of freedom	6
Joint configuration	Six revolute joints
Installation	Floor or ceiling; wall-mounted as a customised configuration
Rated payload	2 kg
Maximum payload	3 kg
Maximum reach radius	649 mm
Position repeatability	±0.02 mm
Drive system	AC servo motors
Position detection	Absolute encoders
Robot mass	21 kg
Compatible controller	CR800-02VD, standalone configuration

The robot has six revolute joints, denoted by J1–J6, which provide the rotational motions required for positioning and orienting the end effector. The permitted angular displacement of each joint is defined by its mechanical and control limitations. The operating ranges of the individual joints are presented in Table 2.

In addition to the individual joint limits presented in Table 2, the overall dimensions and operating envelope of the robot are shown in Figure 2.

Table 2 Operating ranges of the Mitsubishi RV-2FRL joints

Joint	Functional description	Minimum angle	Maximum angle	Total operating range
J1	Base rotation	−240°	+240°	480°
J2	Shoulder rotation	−117°	+120°	237°
J3	Elbow rotation	0°	+160°	160°
J4	Wrist rotation	−200°	+200°	400°
J5	Wrist bending	−120°	+120°	240°
J6	Tool-flange rotation	−360°	+360°	720°

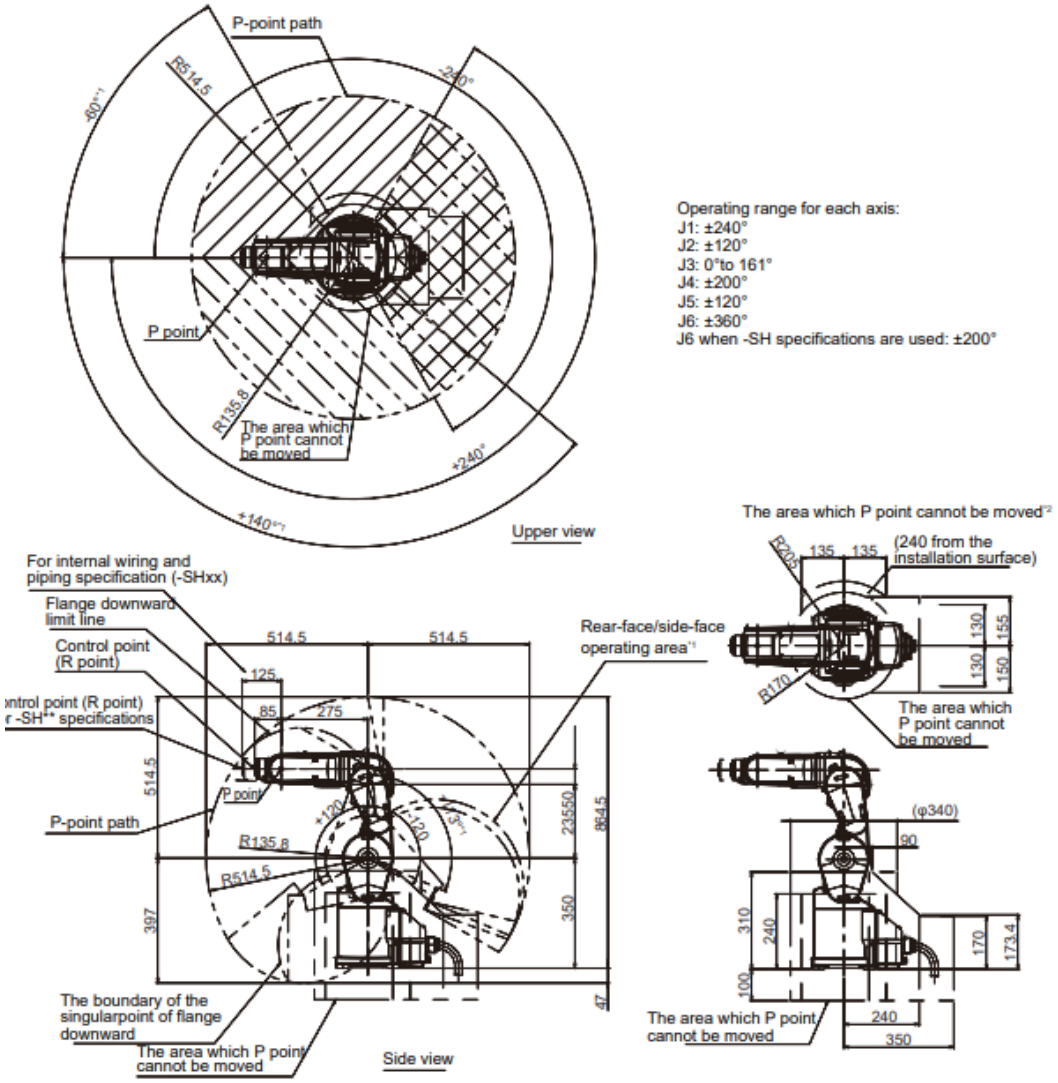


Figure 2 Overall dimensions and operating envelope of the Mitsubishi RV-2FRL robot [9]

Among the six joints, the J4 axis is selected for the analysis presented in this study. According to the manufacturer's specifications, the permissible torque of the J4 axis is 4.17 N·m, while the maximum permissible load inertia about this axis is 0.18 kg·m² (Mitsubishi Electric, 2020). In the proposed model, the latter value is adopted as the reference moment of inertia of the mechanical load. The J4 axis therefore provides the link between the technical characteristics of the original robotic system and the subsequent analysis of hydraulic actuation as an alternative drive solution.

Alternative Hydraulic Actuation of the J4 Axis

Although the Mitsubishi RV-2FRL is originally actuated by AC servo motors, the present study considers a hydrostatic servo drive as an alternative actuation concept for its J4 axis. Both electric and hydraulic servo drives

are governed by the mechanical equilibrium of the actuated joint, in which the drive torque must overcome the effects of inertia, friction, and external loading. However, the physical processes through which the driving torque is generated differ considerably. In an electric drive, torque is produced by an electric motor, whereas in a hydrostatic drive it results from the pressure difference across a hydraulic motor.

The analysis of hydraulic actuation is particularly relevant for robotic systems operating under demanding load conditions. Hydrostatic drives can generate high forces and torques while maintaining a favorable power-to-weight ratio, which makes them suitable for heavy-duty manipulators and other systems requiring high load capacity (Merritt, 1967). Nevertheless, their application to small precision robots is more challenging because fluid compressibility, leakage, and servo-valve dynamics may adversely affect the transient response and positioning performance.

Accordingly, the Mitsubishi RV-2FRL is used in this study as a reference platform for examining whether a hydrostatic servo drive can satisfy the dynamic requirements of a compact industrial robot. The J4 axis is selected because its technical parameters are available in the manufacturer's documentation and can be directly incorporated into the proposed mathematical model. The maximum permissible load inertia of 0.18 kg·m² specified for this axis is adopted as the reference value of the mechanical-load inertia. The influence of an increased load is subsequently examined by varying the moment of inertia up to 0.50 kg·m² (Mitsubishi Electric, 2020; Човић & Лазаревић, 2008).

Although hydrostatic drives are most commonly associated with heavy-duty industrial applications, they are also widely used in the automotive industry, particularly in vehicle steering systems, active suspension systems, braking systems, and robotic manipulators used in automotive assembly lines. The proposed approach is therefore directly applicable to automotive manufacturing environments where a high force-to-weight ratio and precise motion control are required.

Mathematical Model of the Hydrostatic Servo System

The proposed hydrostatic servo system is represented as a coupled system comprising four principal components: a servo valve, a hydraulic motor, a rotating mechanical load, and the hydraulic fluid volume contained in the connecting lines between the valve and the motor. The mathematical model is derived by combining the equations governing rotational motion, hydraulic motor behavior, servo-valve dynamics, and fluid-flow continuity.
To obtain a tractable transfer-function model, several simplifying assumptions are introduced. The system parameters are assumed to remain constant within the considered operating range, the hydraulic fluid properties are treated as uniform, and the servo valve is assumed to operate within its linear region. The effects of fluid compressibility and internal leakage are initially included in the complete model and subsequently neglected when deriving the reduced-order model. The model is linearized about a nominal operating point, and zero initial conditions are assumed when applying the Laplace transformation.

Mechanical and Hydraulic Actuator Dynamics

The mechanical subsystem comprises the hydraulic motor shaft and the attached rotating load. Its rotational dynamics are described using Newton's second law for rotational motion:

$$J \cdot \ddot{\theta}_m + B \cdot \dot{\theta}_m = T_m - T_L \,, \tag{1}$$

where J is the total moment of inertia of the motor and the mechanical load, B is the viscous damping coefficient, θ_m is the angular displacement of the motor shaft, T_m is the torque generated by the hydraulic motor, and T_L is the externally applied load torque.

Applying the Laplace transformation to Equation (1), under zero initial conditions, gives:

$$\left(J_S^2 + B_S\right) \cdot \theta_m(S) = T_m(S) - T_L(S) \,. \tag{2}$$

The relationship between the angular displacement of the motor shaft and the acting torques can then be expressed as:

$$\theta_m(S) = \frac{T_m(S) - T_L(S)}{J_S^2 + B_S} \,. \tag{3}$$

The hydraulic motor converts hydraulic energy, supplied in the form of pressurised fluid flow, into mechanical rotational energy. Under idealised operating conditions, the torque generated by the motor is proportional to the pressure difference across the motor:

$$T_m = D_m \cdot P_L \,, \tag{4}$$

where D_m is the hydraulic motor displacement, expressed in m³/rad, and (P_L=P_1-P_2) is the pressure difference between the motor inlet and outlet, expressed in Pa.
The theoretical flow required by the hydraulic motor is proportional to the angular velocity of its shaft:

$$Q_m = D_m \cdot \dot{\theta}_m \,. \tag{5}$$

Equations (4) and (5) establish the coupling between the hydraulic and mechanical domains of the proposed drive system.

Servo-Valve Dynamics and Flow Continuity

The servo valve regulates the direction and rate of hydraulic fluid flow supplied to the motor. Within the linear operating range, its dynamics can be approximated using a first-order transfer function (Jelali & Kroll, 2003):

$$\frac{X_v(S)}{U(S)} = \frac{K_v}{\tau_v \cdot s + 1} \,, \tag{6}$$

where xv is the valve-spool displacement, U is the control voltage, Kv is the servo-valve gain, and tv is the servo-valve time constant.

Assuming linearized operation around the selected working point, the valve flow is proportional to the spool displacement:

$$Q_V = K_q \cdot X_v \,, \tag{7}$$

where Kq is the valve flow gain. Combining Eq. (6) and (7) yields the transfer function relating the valve flow to the control signal:

$$\frac{Q_v(S)}{U(S)} = \frac{K_V \cdot K_q}{\tau_V \cdot s + 1} = \frac{K_Q}{\tau_V \cdot s + 1} \,, \tag{8}$$

where (K_Q=$K_v K_q$) represents the overall valve flow gain.

The flow-continuity equation describes the balance between the flow supplied by the servo valve, the flow consumed by the hydraulic motor, the flow associated with fluid compression, and internal leakage (Blackburn et al., 1960; Nichols & Reistad, 1999):

$$Q_v(S) = Q_m + Q_C + Q_l \,, \tag{9}$$

where Q_v is the flow supplied by the servo valve, Q_m is the flow required by the hydraulic motor, Q_c is the flow associated with hydraulic fluid compression, and Q_l is the internal leakage flow.

The flow component resulting from fluid compressibility is expressed as:

$$Q_C = \frac{V_t}{4 \cdot \beta_e} \cdot \frac{dP_L}{dt} \,, \tag{10}$$

where V_t is the total effective fluid volume between the servo valve and the hydraulic motor and β_e is the effective bulk modulus of the hydraulic fluid.

The internal leakage flow is represented by the following linearized relationship:

$$Q_l = K_l \cdot P_L \,, \tag{11}$$

where K_l is the internal leakage coefficient. Combining Equations (5), (9), (10), and (11) gives:

$$Q_v = D_m \cdot s \cdot \dot{\theta}_m + \frac{V_t}{4 \cdot \beta_e} \cdot \dot{P}_L + K_l \cdot P_L \,. \tag{12}$$

Applying the Laplace transformation to Equation (12), under zero initial conditions, yields:

$$Q_v(s) = D_m \cdot s \cdot \theta_m(s) + \left(\frac{V_t}{4 \cdot \beta_e} s + K_l \right) \cdot P_L(s) . \tag{13}$$

Overall Transfer Function and Reduced-Order Model

The overall mathematical model is obtained by combining the mechanical-load dynamics, the hydraulic motor relationships, the servo-valve transfer function, and the fluid-flow continuity equation. The transformed equation of rotational motion is first rearranged as:

$$T_m(s) = \left(J \cdot s^2 + B \cdot s \right) \theta_m(s) + T_L(s) . \tag{14}$$

Substitution of the hydraulic motor torque relationship from Eq. (4) into Eq. (14) gives:

$$D_m P_L(s) = \left(J \cdot s^2 + B \cdot s \right) \theta_m(s) + T_L(s) . \tag{15}$$

The resulting expression for the load pressure is:

$$P_L(s) = \frac{\left(J \cdot s^2 + B \cdot s \right) \theta_m(s) + T_L(s)}{D_m} . \tag{16}$$

The valve flow is then obtained from Equation (13):

$$Q_v(s) = D_m \cdot s \cdot \theta_m(s) + \left(\frac{V_t}{4 \cdot \beta_e} s + K_l \right) P_L(s) . \tag{17}$$

Substituting Equation (16) into Equation (17) and assuming $T_L=0$ gives:

$$Q_v(s) = \left[D_m s + \left(\frac{V_t}{4 \cdot \beta_e} s + K_l \right) \frac{J \cdot s^2 + B \cdot s}{D_m} \right] \cdot \theta_m(s) , \tag{18}$$

$$\frac{Q_m(s)}{Q_v(s)} = \frac{1}{D_m s + \left(\frac{V_t}{4 \cdot \beta_e} s + K_l \right) \frac{J \cdot s^2 + B \cdot s}{D_m}} , \tag{19}$$

$$\frac{Q_m(s)}{Q_v(s)} = \frac{D_m}{J \cdot \frac{V_t}{4 \cdot \beta_e} \cdot s^3 + \left(\frac{V_t \cdot B}{4 \cdot \beta_e} + J \cdot K_l \right) \cdot s^2 + \left(B \cdot K_l + D_m^2 \right) \cdot s} . \tag{20}$$

The condition $T_L=0$ indicates that no additional external disturbance torque is applied during the analysis. It does not imply the absence of mechanical loading, because the effects of the motor and load inertia remain included through the parameter J.

By incorporating the servo-valve relationship defined by Equation (8), the overall transfer function between the control signal $U(s)$, and the angular position of the motor shaft $\theta_m(s)$, is obtained:

$$G(s) = \frac{Q_m(s)}{U(s)} = \frac{K_Q \cdot D_m}{a_3 \cdot s^3 + a_2 \cdot s^2 + a_1 \cdot s + a_0} . \tag{21}$$

The denominator coefficients of the transfer function are defined as:

$$\frac{Q_m(s)}{Q_v(s)} = \frac{D_m}{J \cdot \frac{V_t}{4 \cdot \beta_e} \cdot s^3 + \left(\frac{V_t \cdot B}{4 \cdot \beta_e} + J \cdot K_l \right) \cdot s^2 + \left(B \cdot K_l + D_m^2 \right) \cdot s} . \tag{22}$$

$$a_3 = J \cdot \frac{V_t}{4 \cdot \beta_e} \; ; \; a_2 = \left(\frac{V_t \cdot B}{4 \cdot \beta_e} + J \cdot K_l \right) \cdot \tau_v \; ; \; a_1 = \left(B \cdot K_l + D_m^2 \right)$$

The complete transfer function includes the effects of servo-valve dynamics, mechanical inertia, viscous damping, fluid compressibility, and internal leakage. It therefore provides the basis for analysing the dynamic response of the proposed hydrostatic servo drive under different operating conditions.

For a preliminary assessment of the dominant system dynamics, a reduced-order model is also considered. By neglecting the effects of fluid compressibility and internal leakage, the complete transfer function is reduced to a second-order form:

$$\frac{Q_m(s)}{Q_v(s)} = \frac{D_m}{s(J \cdot s + B) + D_m^2 \cdot \tau_v \cdot s + D_m^2} = \frac{D_m}{J \cdot s^2 + (B + D_m^2 \cdot \tau_v) \cdot s + D_m^2}, \tag{23}$$

$$G_2(s) = \frac{Q_m(s)}{U(s)} = \frac{K_Q \cdot D_m}{J \cdot s^2 + (B + D_m^2 \cdot \tau_v) \cdot s + D_m^2}. \tag{24}$$

This simplification enables a direct assessment of the influence of the mechanical-load inertia and servo-valve time constant on the dominant transient behaviour of the system. The corresponding second-order characteristic equation is:

$$J \cdot s^2 + (B + D_m^2 \cdot \tau_v) \cdot s + D_m^2 = 0. \tag{25}$$

2.4. Evaluation of the Transient Response

The transient response of the proposed hydrostatic servo drive is evaluated using its response to a unit-step control input. For the second-order model defined by Equation (25), the settling time within a ±2% tolerance band can be approximated as:

$$t_s \approx \frac{4}{\zeta \cdot \omega_n}, \tag{26}$$

where $\omega_n = \sqrt{\frac{D_m^2}{J}}$ – is the undamped natural frequency and $\zeta = \frac{B + D_m^2 \cdot \tau_v}{2 \cdot \sqrt{J \cdot D_m^2}}$ – is the damping ratio of the equivalent second-order system.

The analytical expression for the settling time is applicable when the transient response is dominated by a pair of underdamped complex-conjugate poles. For the complete third-order model defined by Eq. (21), the settling time is determined numerically from the simulated unit-step response. The numerical analysis is performed in MATLAB using Control System Toolbox (MathWorks, 2024).

MATLAB Implementation and Simulation Procedure

Based on the derived mathematical model, including the complete transfer function given by Eq. (21) and the reduced-order model defined by Eq. (25), the dynamic response of the proposed hydrostatic servo system was simulated in MATLAB R2024a using Control System Toolbox (MathWorks, 2024). The simulations were performed to quantify the effects of the servo-valve time constant t_v and the total moment of inertia J on the transient response of the system.

The nominal parameter values adopted for the simulations are presented in Table 3. The reference moment of inertia, (J=0.18 kg·m^2), corresponds to the maximum permissible load inertia specified by the manufacturer for the J4 axis of the Mitsubishi RV-2FRL robot (Mitsubishi Electric, 2020). The remaining hydraulic parameters were selected from representative values reported in the literature and were kept constant throughout the parametric analysis (Merritt, 1967; Jelali & Kroll, 2003).

The mathematical model was implemented in MATLAB by defining the nominal system parameters and calculating the transfer-function coefficients according to Eq. (22). The transfer function was then created using the tf function, while the response to a unit-step input was obtained using the step function. The transient-response characteristics were determined using step info, with the settling-time threshold set to 2%.

Two sets of simulations were performed. In the first set, the total moment of inertia was maintained at its reference value of (J=0.18 kg·m^2), while the servo-valve time constant was varied from 5 to 50 ms. For each value of t_v, the transfer-function coefficients were recalculated and the corresponding unit-step response was obtained. This

analysis was conducted to determine how the dynamic response of the servo valve affects the settling time and overshoot of the complete drive system.

Table 3 Nominal parameters of the hydrostatic servo-system model

Parameter	**Value**
Reference moment of inertia (J), kg·m²	0.18
Viscous damping coefficient (B), N·m·s/rad	0.01
Hydraulic motor displacement (D_m), m³/rad	$5 \cdot 10^{-6}$
Effective bulk modulus (β_e), Pa	$1.2 \cdot 10^{9}$
Total fluid volume between the valve and motor (v_t), m³	$50 \cdot 10^{-6}$
Overall valve flow gain (K_Q), m³/(s·V)	$1 \cdot 10^{-6}$
Internal leakage coef m³/(s·Pa)ficient (K_l),	$1 \cdot 10^{-12}$

In the second set of simulations, the servo-valve time constant was fixed at t_v=10 ms, while the moment of inertia was varied from 0.18 to 0.50 kg·m². The lower limit corresponds to the maximum permissible load inertia specified for the J4 axis, whereas the higher values represent increased equivalent mechanical loading considered for the purpose of the parametric analysis. This simulation set was used to evaluate the influence of mechanical inertia on the transient response of the proposed drive.

For both simulation sets, the settling time was defined as the time after which the system response remained within ±2% of its final value. Overshoot was also monitored to provide a more complete assessment of the transient behaviour.

3. RESULTS AND DISCUSSION

The simulated unit-step responses were first analysed for different values of the servo-valve time constant t_v, while the moment of inertia was maintained at its reference value of J=0.18 kg·m^2. The servo-valve time constant was varied from 5 to 50 ms to evaluate the influence of valve dynamics on the transient response of the proposed hydrostatic drive.

Figure 3 presents the unit-step responses obtained for the four considered values of t_v. An increase in the servo-valve time constant produced a progressively slower response. For t_v =5 ms, the system entered and remained within the specified ±2% tolerance band after approximately 0.145 s. When the time constant was increased to 50 ms, the settling time increased to 0.316 s.

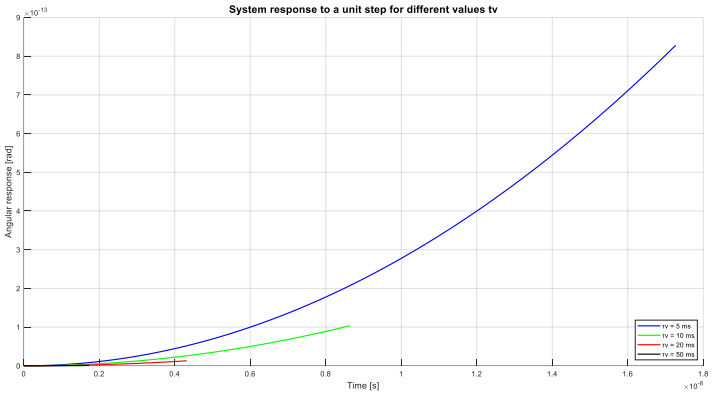


Figure 3 Unit-step responses of the system for different servo-valve time constants at J=0.18 kg·m^2

The calculated settling times are summarised in Table 4. The relative increase was determined with respect to the response obtained for t_v =5 ms.

Table 4 Settling time as a function of the servo-valve time constant

t_v, ms	**Settling time t_s, s**	**Relative increase, %**
5	0.145	–
10	0.178	22.8
20	0.235	62.1
50	0.316	117.9

Increasing t_v from 5 to 50 ms increased the settling time by approximately 118%. This result demonstrates that the servo-valve dynamics have a pronounced influence on the speed of the system response. A larger time constant

corresponds to a slower valve response and introduces a slower dynamic component into the overall system. The observed relationship is monotonic but not uniformly linear over the entire investigated range, as the incremental change in settling time decreases at higher values of t_v.

The influence of the mechanical-load inertia was subsequently examined by fixing the servo-valve time constant at t_v =10 ms and varying the moment of inertia from 0.18 to 0.50 kg·m² (Figure 4).

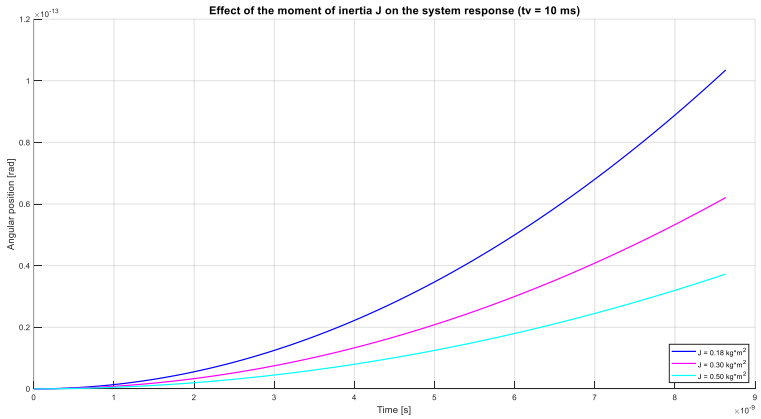


Figure 4. Unit-step responses of the system for different moments of inertia at J=0.18 kg·m²

The calculated settling times are presented in Table 5. The relative changes were determined with respect to the reference value J=0.18 N·kg·m².

Table 5 Settling time as a function of the moment of inertia

J, kg·m²	**Settling time t_s, s**	**Relative increase, %**
0,18	0,178	-
0,30	0,218	22,5
0,50	0,281	57,9

An increase in the moment of inertia from 0.18 to 0.50 kg·m² increased the settling time by approximately 58%. This behaviour is consistent with the mechanical interpretation of the system, because a larger equivalent inertia requires a greater drive torque to achieve the same angular acceleration. In the considered robotic application, an increase in the payload or a change in its position relative to the joint axis increases the equivalent load inertia and consequently reduces the speed of the transient response.

The results obtained from the two parametric simulation sets demonstrate that both the servo-valve time constant and the equivalent mechanical-load inertia influence the settling time of the system. Within the considered parameter ranges, increasing the servo-valve time constant produced a larger relative change in settling time than increasing the moment of inertia. However, this comparison applies only to the selected ranges and nominal values and should not be interpreted as a general ranking of parameter sensitivity (Saltelli et al., 2008).

The accuracy of the reduced-order model was evaluated by comparing its response with that of the complete third-order model for the nominal parameter values J=0.18 kg·m² and t_v=10 ms (Figure 5).

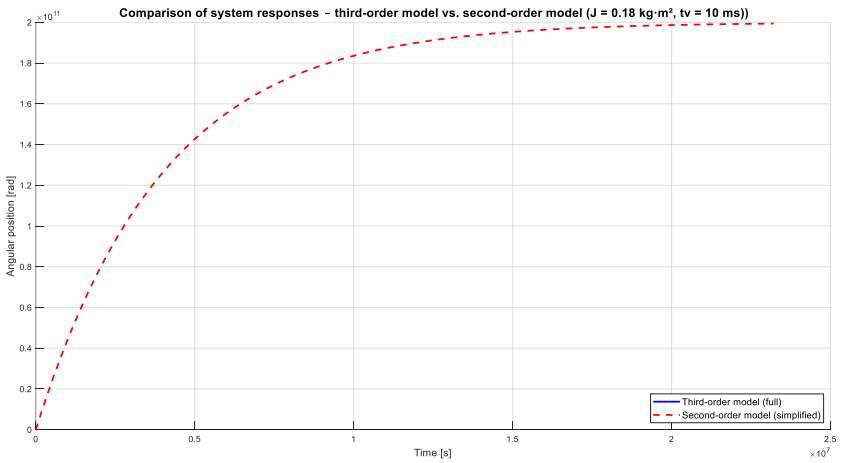


Figure 5 Comparison of the unit-step responses obtained using the complete third-order model and the reduced second-order model for J=0.18 kg·m² and t_v=10 ms

The responses of the two models were in close agreement under the nominal operating conditions. The maximum relative difference was 1.85%, while the mean error was 0.42%. Figure 6 presents the absolute and relative differences between the responses over the analysed simulation interval.

The obtained agreement indicates that the reduced second-order model provides an acceptable approximation of the dominant dynamics under the considered nominal conditions. For the adopted parameter values, the effects represented by the additional dynamics of the complete model have only a limited influence on the simulated unit-step response. The reduced model can therefore be used for a preliminary assessment of settling time and dominant transient behaviour (Watton, 1989; Chapple, 2010).

Nevertheless, this conclusion is limited to the investigated parameter set. Further simulations over wider ranges of the effective bulk modulus, fluid volume, and leakage coefficient would be required before concluding that fluid compressibility and leakage are negligible under all operating conditions. The complete model remains more appropriate when these effects are expected to become significant (Jelali & Kroll, 2003).

The results obtained from the two parametric simulation sets demonstrate that both the servo-valve time constant and the equivalent mechanical-load inertia influence the settling time of the system. Within the considered parameter ranges, increasing the servo-valve time constant produced a larger absolute relative change in settling time than increasing the moment of inertia. However, the parameters were varied over considerably different relative ranges. Therefore, the relative increases in settling time alone cannot be used to compare their proportional influence (Saltelli et al., 2008).

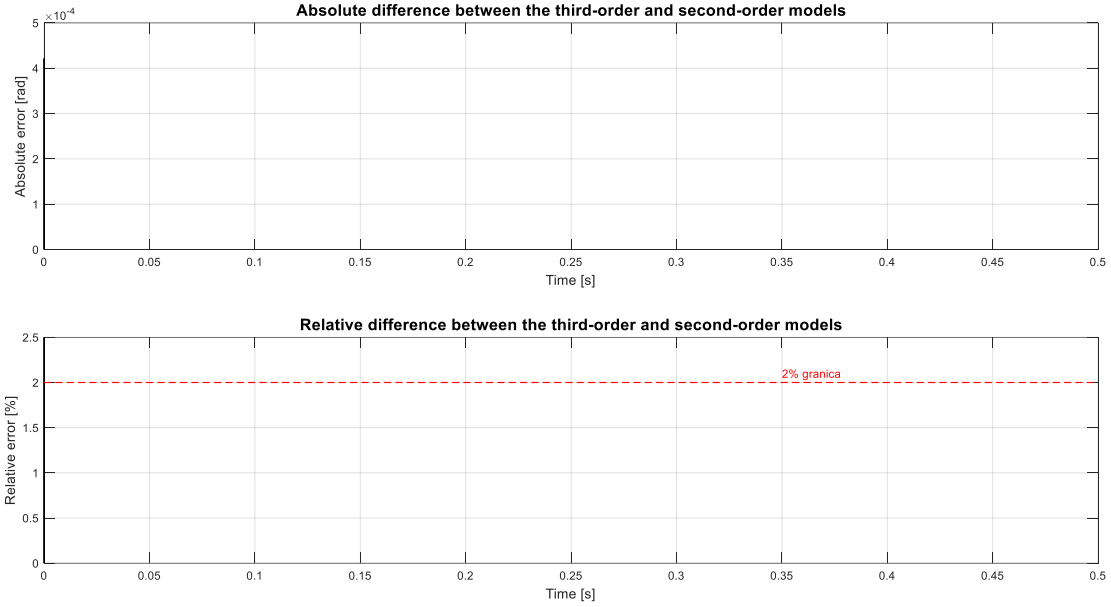


Figure 6 Absolute and relative differences between the responses of the complete and reduced-order models

To provide a normalised comparison, a sensitivity analysis was performed for the two investigated parameters. The normalised sensitivity of the settling time t_s to a parameter x was defined as (Saltelli et al., 2008):

$$S_x^{t_s} = \frac{\partial t_s}{\partial x} \cdot \frac{x}{t_s}, \tag{27}$$

The coefficient is dimensionless and expresses the relative change in settling time resulting from a relative change in the considered parameter. Since the relationship between the settling time and the investigated parameters was obtained numerically, the derivative in Equation (27) was approximated using the changes between the initial and final simulated values. The initial parameter value and its corresponding settling time were used as reference values. The calculated sensitivity coefficients are presented in Table 6.

Table 6 Relative sensitivity of the settling time to the investigated parameters

Parameter	Investigated range	Settling-time range	Sensitivity coefficient
t_v, ms	5 - 50	0.145–0.316 s	0.13
J, kg·m^2	0.18 – 0.50	0.178–0.281 s	0.33

These findings have practical implications for the design of hydrostatic servo drives for robotic applications. A faster transient response can be achieved by limiting the equivalent moment of inertia and selecting a servo valve with a small time constant. The equivalent inertia can be reduced by limiting the payload, positioning it closer to the joint

axis, and reducing the mass of the moving components. Conversely, an increase in payload, particularly when it is positioned farther from the joint axis, increases the equivalent moment of inertia and adversely affects the dynamic response of the system (Човић & Лазаревић, 2008).

The calculated coefficients represent average relative sensitivities over the investigated parameter intervals and should not be interpreted as local sensitivity coefficients at the nominal operating point. Nevertheless, they provide a concise quantitative comparison of the two parameters considered in this study (Saltelli et al. 2008).

4. CONCLUSION

In this study, a mathematical model of a hydrostatic servo system was developed to analyze the dynamic behavior of a rotary joint drive, using the J4 axis of the Mitsubishi RV-2FRL industrial robot as a reference application. A linearized third-order transfer function relating the servo-valve control signal to the angular position of the output shaft was derived by combining the mechanical-load dynamics, hydraulic motor behavior, servo-valve dynamics, and fluid-flow continuity. A reduced second-order model was also considered to enable a simplified assessment of the dominant system dynamics.

The effects of the servo-valve time constant t_v, and the equivalent moment of inertia J on the transient response were evaluated in MATLAB using unit-step simulations. Increasing t_v from 5 to 50 ms increased the settling time from 0.145 to 0.316 s, corresponding to an increase of approximately 118%. Increasing J from 0.18 to 0.50 kg·m², at t_v =10 ms, increased the settling time from 0.178 to 0.281 s, corresponding to an increase of approximately 58%. These results confirm that both servo-valve dynamics and equivalent mechanical loading have a pronounced influence on the response speed of the proposed drive.

The normalized sensitivity coefficients calculated over the investigated parameter intervals were 0.33 for the moment of inertia and 0.13 for the servo-valve time constant. Therefore, relative to the magnitude of the applied parameter variation, the settling time was more sensitive to changes in the equivalent moment of inertia. This finding indicates that payload magnitude, payload position relative to the joint axis, and the mass of the moving components must be considered together with the dynamic characteristics of the selected servo valve.

The comparison between the complete third-order model and the reduced second-order model showed a maximum relative difference of 1.85% and a mean error of 0.42% under the considered nominal conditions. The reduced model therefore provides an acceptable approximation of the dominant transient behavior for preliminary analysis and component selection. However, this conclusion is limited to the adopted parameter values and does not imply that fluid compressibility and leakage can be neglected under all operating conditions.

The obtained results indicate that hydrostatic actuation has theoretical potential as an alternative drive solution for the considered robotic joint, provided that a sufficiently fast servo valve is employed and the equivalent mechanical-load inertia is appropriately limited. Within the investigated range, servo valves with smaller time constants produced considerably faster responses. Nevertheless, the unit-step response and settling time alone are not sufficient to confirm that the original positioning repeatability of the Mitsubishi RV-2FRL can be maintained. Experimental validation and an evaluation of positioning error, disturbance rejection, and closed-loop performance are required before the practical feasibility of the proposed drive can be confirmed.

Future research will focus on experimental validation of the developed model, the identification of hydraulic parameters using a physical test system, and the development of an appropriate closed-loop control strategy. The model may also be extended to include nonlinear valve characteristics, pressure-dependent fluid properties, friction, variable payloads, and joint-dependent loading conditions.

ACKNOWLEDGMENTS

The research results presented in this paper were obtained within projects financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under Contract No. 451-03-34/2026-03/200107, dated 5 February 2026.

REFERENCES

Blackburn, J. F., Reethof, G., & Shearer, J. L. (1960). *Fluid Power Control*. Cambridge, USA: The M.I.T. Press.

Chapple, J. P. (2010). Hydraulic servo system modelling and simulation. In *Proceedings of the 5th International Conference on Fluid Power* (pp. 45–52). Florence, Italy, 15–17 April 2010.

Човић, В., & Лазаревић, М. П. (2008). Механика робота. Београд, Србија: Машински факултет.

Jelali, M., & Kroll, A. (2003). *Hydraulic Servo-systems: Modelling, Identification and Control*. London, UK: Springer.

MathWorks. (2024). *Control System Toolbox Documentation*. Natick, USA: The MathWorks Inc.

Merritt, H. E. (1967). *Hydraulic Control Systems*. New York, USA: John Wiley & Sons.

Merritt, H. (1971). *Hydraulic servo systems*. Machine Design, 43(15), 92–99.

Mitsubishi Electric. (2020). MELFA RV-2FRL Series Standard Specifications Manual. Mitsubishi Electric Corporation.

Nichols, B. L., & Reistad, H. M. (1999). *Hydraulic servo systems*. In M. R. Adams (Ed.), Fluid Power Design Handbook (3rd ed., pp. 245–289). New York, USA: Marcel Dekker.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). *Global Sensitivity Analysis: The Primer*. Chichester, UK: John Wiley & Sons.

Watton, J. (1989). *Fluid Power Systems: Modeling, Simulation, Analog and Microcomputer Control*. Hemel Hempstead, UK: Prentice Hall.


9 788663 351325