Engineering Science and Technology, an International Journal 19 (2016) 1514–1525

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Modeling and analysis of hydraulic dashpot for impact free operation in a shut-off rod drive mechanism

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ARTICLE INFO

Article history:
Received 29 December 2015
Revised 11 May 2016
Accepted 11 May 2016
Available online 21 May 2016

Keywords:
Hydraulic dashpot
Rigid body dynamics
Nuclear reactor
Reactor control mechanism
Rod drop profile
Shut-off rods

ABSTRACT

Rotary hydraulic dashpot used for shut-off rod drive mechanism application of a nuclear reactor has been studied in this paper for impact free operation. The rotary hydraulic dashpot has been modeled as a system with 1 degree of freedom (DOF) and the simulation results are experimentally validated. The dashpot is modeled as a hinge joint with moving and fixed vanes as rigid bodies. Shut-off rods are used to shutdown a nuclear reactor and hydraulic dashpot absorbs the energy of freely falling shut-off rod at the end of rod travel. With the increase in the environmental temperature the dashpot becomes underdamped at a point because of reduction in the viscosity of oil and results into impact on mechanism components. Hydraulic dashpot designs are finalized with an optimum combination of dashpot clearances and oil viscosity to meet the drop time criterion and impact free operation at room temperature as well as at elevated temperature. Also with the change in mechanical loads the dashpot becomes underdamped. So the study is further extended to see the effects of various parameters such as moment of inertia, constraint angle and applied moment on the dashpot. Study is focused on obtaining dashpot responses in terms of relative rotation, relative angular velocity and relative angular acceleration at various environmental temperatures. Finite element commercial code COMSOL Multiphysics 5.1 has been used for numerical simulations. Equations for both rigid body dynamics and heat transfer in solids are solved simultaneously. Thus, energy absorbed and local temperature rise in the dashpot operation is also obtained. Both simulation and experimental results at wide range of environmental temperature are presented and compared in this paper. This study forms a good tool to design a hydraulic dashpot, which gives impact free operation in a shut-off rod free fall.

1. Introduction

Nuclear reactors are shut-down by inserting shut-off rods inside the reactor core and these rods are moved using shut-off rod drive mechanisms (SRDM). At the time of reactor start-up, rods are withdrawn at a given speed and are held in position during the reactor operation. On demand, shut-off rods fall freely into the reactor core. However, at the end of rod travel, rod velocity is smoothly brought to zero using a passive device called as 'Hydraulic Dashpot'. In this, damping oil is allowed to flow from one chamber to the other through narrow clearances, giving damping action. After dashpot engagement, there is a sudden pressure built-up inside the high pressure chamber and thereafter it reduces at the end of travel as oil passes to low pressure chamber through narrow clearances. The hydraulic dashpot vanes rotate typically by 120° in one rod drop cycle. General arrangement of SRDM along with the guide tube components is given in Fig. 1. The detailed study of dashpot pressure and damping force in the hydraulic dashpot is presented in Singh et al. [1]. These mechanisms are to be qualified at room temperature during reactor start-up as well as at elevated temperature during reactor operation, where heat comes from environment. Hydraulic dashpot designs are finalized with an optimum combination of dashpot clearances and oil viscosity. These hydraulic dashpots are a part of safety critical system, hence required to operate in a passive manner. Active shock absorbers like based on magneto-rheological (MR) fluids as given by Kumbhar et al. [2] are not suitable for shut-off rod drive mechanism applications.

Wenzer [3] has done the analysis of dashpot performance for rotating control drums of a lithium cooled fast reactor concept, where with manual calculation the available torque was calculated at every time step and dashpot rotational velocity vs time curves

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.05.005
2215-0986/

Nomenclature

A	total vane area
cc	cubic centimeter
C_p	specific heat capacity at constant pressure
°C	degree Celsius
c_θ	damping coefficient
cst	centistokes
Fig.	figure
$\mathbf{I}$	unit matrix
J	Joule
I_e	effective moment of inertia at the joint
I_{src}	source moment of inertia
I_{dest}	destination moment of inertia
ID	inner diameter
k	coefficient of thermal conductivity
°K	degree Kelvin
kg	kilogram
k_θ	spring constant
m	meter
mm	millimeter
M	total dashpot moment
M_d	damping moment
N	Newton
No.	number
OD	outer diameter
p	pressure
p_u	penalty factor
Pa	Pascal
Q	heat sources
$\mathbf{R}$	rotation matrix
R_t	torque arm
rad	radian
$\mathbf{R}_{\mathrm{src}}$	rotation matrices describing the rotation of source attachments
$\mathbf{R}_{\mathrm{dest}}$	rotation matrices describing the rotation of destination attachments
s	second
t	time
T	absolute temperature
T_q	torque
$\mathbf{u}$	displacement field
$\mathbf{u}_{\mathrm{con}}$	convective velocity field
$\mathbf{u}_{\mathrm{c.src}}$	displacement vectors for source attachments
$\mathbf{u}_{\mathrm{c.dest}}$	displacement vectors for destination attachments
$\mathbf{u}_{\mathrm{src}}$	displacements at the centroid of the source attachments
$\mathbf{u}_{\mathrm{dest}}$	displacements at the centroid of the destination attachments
V	volt
$\mathbf{X}_{\mathrm{c}}$	joint center
$\mathbf{X}_{\mathrm{c.src}}$	positions of centroids for source attachments
$\mathbf{X}_{\mathrm{c.dest}}$	positions of centroids for destination attachments
w.r.t.	with respect to
W	Watt
W_d	energy dissipation rate

Greek symbols

ρ	density of fluid
∇	divergence
Φ_{src}	rotation about the axis for source attachments
Φ_{dest}	rotation about the axis for destination attachments
ω	angular velocity
θ	relative rotation
θ_0	pre-deformation

Abbreviation

AHWR	advanced heavy water reactor
CFD	computational fluid dynamics
DOF	degree of freedom
EM	electro-magnetic
MWe	megawatt electric
PHWR	pressurized heavy water reactor
RPM	rotation per minute
SRDM	shut-off rod drive mechanism

were generated. With advancement in computational techniques, various researchers have developed damper models and simulations were done. Suresh et al. [4] has done the performance analysis of oil dashpot in control and safety rod drive mechanism. Analysis is done by mathematical modeling of dashpot system as spring mass damper two degree of freedom system. A basic model of a control assembly drop in nuclear reactors is given by Bulin et al. [5]. They have proposed two models; one is a simple rigid body model intended for basic dynamic analysis and other is based on complex multibody model. Allen et al. [6] have developed a damper model for use in multi-body model for use in multi-body dynamic simulations. In this study a warrior armoured personnel carrier rotary damper is modeled. They also studied the responses of damper at different flow regimes. Lion and Loose [7] have given a thermo-mechanically coupled model for automotive shock absorber. Jingyang et al. [8] have done multi-body dynamic simulation of flapping wing. In this study, the inertial force and inertial moment between the wing and the body are reflected in the simulation model and the multi-body dynamic equation of model is presented. Shabana [9] has done the viscoelastic analysis of multi-body systems using FEM. In his study constraints between components are formulated.

Present study includes modeling of hydraulic dashpot as a system with 1 DOF, simulation, experimental studies and parametric studies. Dashpot response curves in terms of relative rotation; relative angular velocity; and relative angular acceleration are obtained. The study is done to see the performance of the hydraulic dashpot up to 85 °C. The impact in the hydraulic dashpot beyond 55 °C is also studied. Energy absorbed in dashpot and temperature rise is also studied. Simulation and experimental results are compared. Parametric study is also done using dashpot model. The method used to model the hydraulic dashpot and results obtained are novel. This study forms a handy tool to analyze the performance of rotary hydraulic dashpot.

2. Study set-up description

The present study is carried-out on a prototype SRDM and full-scale test set-up meant to qualify the shut-off rod drive mechanism of ‘Critical Facility’ reactor. Shut-off drive mechanism design is to be qualified on a full scale test station as a regulatory guideline, discussed in Singh [10]. In the shut-off rod drive mechanism, internally the motor sub-assembly is connected to a worm gear and an electromagnetic (EM) clutch sub assembly, which is further connected to a sheave through a set of spur gears. Absorber element (shut-off rod) is mounted on the sheave through a wire rope. EM clutch is energized to raise the rod through motor. As soon as the rod reaches the top position, motor is cut-off and the rod remains at that position, due to irreversibility of worm gear design. During reactor scram, the EM clutch is de-energized and rod falls freely