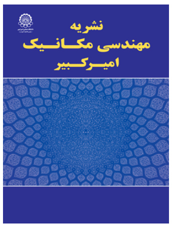

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 54(7) (2022) 301-304
DOI: 10.22060/mej.2022.20658.7288

Numerical Modeling of Diaphragm Dosing Pumps with Fluid-Structure Interaction Analysis

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ABSTRACT: In this paper, the performance of a diaphragm dosing pump of the injection odorizers is simulated with the fluid-structure interaction analysis. The simulation results are validated with experimental data and the largest relative error is 16% for the average flow rate. Performance simulation of the diaphragm pump for the diaphragm oscillation period of 1 second and three different diaphragm displacement amplitudes of 0.8, 0.5, and 0.2 mm, shows that as the amplitude increases, the fluid velocity and consequently the flow rate of the pump increases. The average flow rate of the pump in the mentioned amplitudes is equal to 0.002, 0.0013, and 0.0005 kg/s, respectively. As the amplitude increases from 0.2 to 0.8 mm, the maximum stress applied to the diaphragm increases from 32.2 to 99.2 MPa (equivalent to 208%). Also, the effect of diaphragm oscillation frequency on pump performance is investigated. The results show that the pump's flow rate directly and linearly relates to the diaphragm oscillation frequency. In contrast, the applied stress on the diaphragm is not frequency-dependent and in the same ratios of the period, the applied stress is almost constant. According to the results, if the pump amplitude is set to 0.5 mm and the frequency is 1.6 Hz, instead of operating at a diaphragm amplitude of 0.8 mm and a frequency of 1 Hz, the pump's flow rate will be the same. While the maximum amount of stress in the diaphragm will be reduced by about 30% and the probability of damage will be reduced.

Review History:

Received: Oct. 11, 2021
Revised: Mar. 03, 2022
Accepted: Apr. 16, 2022
Available Online: May, 02, 2022

Keywords:

Diaphragm pumps
Numerical modeling
Fluid-structure interaction
Dosing pumps

1- Introduction

The main components of injection odorizers are diaphragm dosing pumps. These positive displacement pumps use reciprocating deformable diaphragms to produce a pulsating discharge flow. The performance of these pumps depends on the movement of the diaphragm, the operation of the inlet and outlet control valves, and the fluid flow field inside the pump. Given the issues with diaphragm dosing pumps' operation (e.g., diaphragm damage), it is critical to have a precise understanding of their performance. Simulating the operation of these pumps can help identify and investigate the factors that are effective in reducing their damage. Because the operation of these pumps is dependent on the effect of diaphragm displacement and deformation on the fluid flow field, an accurate simulation of their behavior must account for Fluid-Structure Interactions (FSI). Positive displacement pumps have received little research, and the majority of it has focused on other types of positive displacement pumps, such as piston pumps [1], plunger pumps [2], or rotary reciprocating pumps [3]. In the field of diaphragm pumps, Alberto et al. [4] presented an unsteady numerical methodology for the Computational Fluid Dynamics (CFD) simulation of air-operated diaphragm pumps. Pan et al. [5] used FSI modeling to investigate the dynamic characteristics of port valves in a diaphragm pump for exhaust gas treatment systems.

This paper numerically investigates the performance of a diaphragm dosing pump used in injection odorizing systems. A 3-D transient model is applied with finite element and finite volume numerical methods, considering the interaction effects of structural motion on the fluid flow behavior inside the pump. The primary purpose of this paper is to investigate the impact of performance parameters, such as diaphragm displacement amplitude and frequency, on stresses applied to the diaphragm to find a solution to reduce these stresses while maintaining the expected flow.

2- Model Description

Fig. 1 shows a schematic of the investigated geometry. The pump's diaphragm is a stainless steel disc with a thickness of 0.5 mm, the side part of which is fixed, and its surface has an arc oscillating motion with a maximum displacement of 0.8 mm. The governing conservation laws of mass and momentum are given by:

$$\nabla . \vec{V} = 0 \qquad (1)$$

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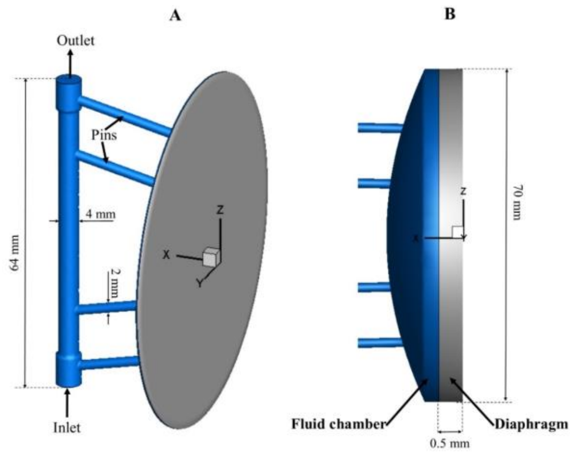

Fig. 1. Schematic of studied geometry (A) 3D simulated geometry with real scale, (B) Fluid chamber and diaphragm in XZ plane which are scaled ten times in the X-direction

$$\rho\left(\frac{\partial \vec{V}}{\partial t}+\vec{V}.\nabla\vec{V}\right)=-\nabla P+\mu\nabla^{2}\vec{V}+\vec{f} \qquad (2)$$

The governing equations for the elastic structural displacement can be written as:

$$\rho_{s}\frac{\partial^{2} d_{s}}{\partial t^{2}}-\nabla\sigma=F_{v} \qquad (3)$$

The governing equations are solved with ANSYS Workbench software. The solid domain is modeled through transient structural analysis using the finite element model. The fluid domain is modeled using a finite volume approximation by FLUENT. The ANSYS system coupling is used to couple Fluent with transient structural to set up a transient coupled FSI.

3- Results and Discussion

Fig. 2 shows the velocity contours in the fluid domain for the diaphragm displacement amplitude of 0.2 mm and time period of 1 s at various times from 0 s to 1 s. This figure is scaled 12 times in the *X*-direction to make the plots easier to view. As shown in Fig. 2, between $t = 0\,\text{s}$ and $t = T/2 = 0.5\,\text{s}$, the diaphragm gradually moves from the initial equilibrium state towards the fluid. During this time, the inlet valve is closed, the outlet valve is open, and the fluid exits the pump. When, at $t = 0.5\,\text{s}$, the diaphragm reaches its maximum displacement, the outlet valve closes, the inlet valve opens, and fluid is drawn from the tank into the pump chamber. Fig. 3 depicts the stress contours in the solid domain for a diaphragm displacement amplitude of 0.2 mm and period of 1 s. This figure is scaled ten times in the *X*-direction and shows that the applied stress on the diaphragm increases over time during the first half of the pump's operation, then gradually decreases.

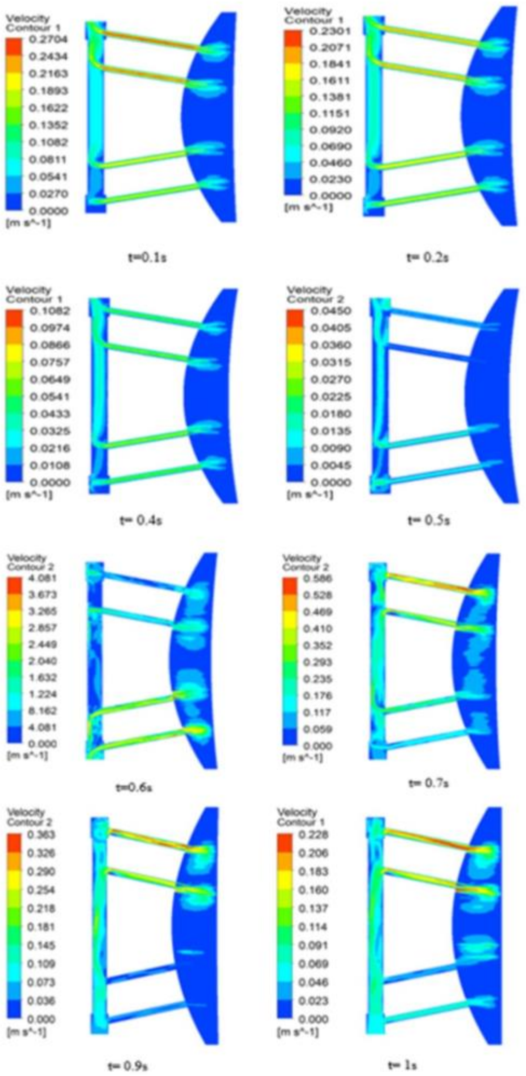

Fig. 2. Velocity contours in the fluid domain for the diaphragm displacement amplitude of 0.2 mm and time period of 1 s at various times from 0 s to 1 s

The effects of diaphragm displacement amplitude and diaphragm oscillation frequency on pump performance are investigated. The results show that by changing the frequency, the maximum stress values in the diaphragm do not change in the same proportions of the period. The highest level of maximum stress occurs at $T/2$ for all periods. Fig. 4 shows the RMS value of mass flow rate and the maximum amount of stress as a function of frequency for the diaphragm displacement amplitude of 0.2, 0.5, and 0.8 mm at $t = T/2$

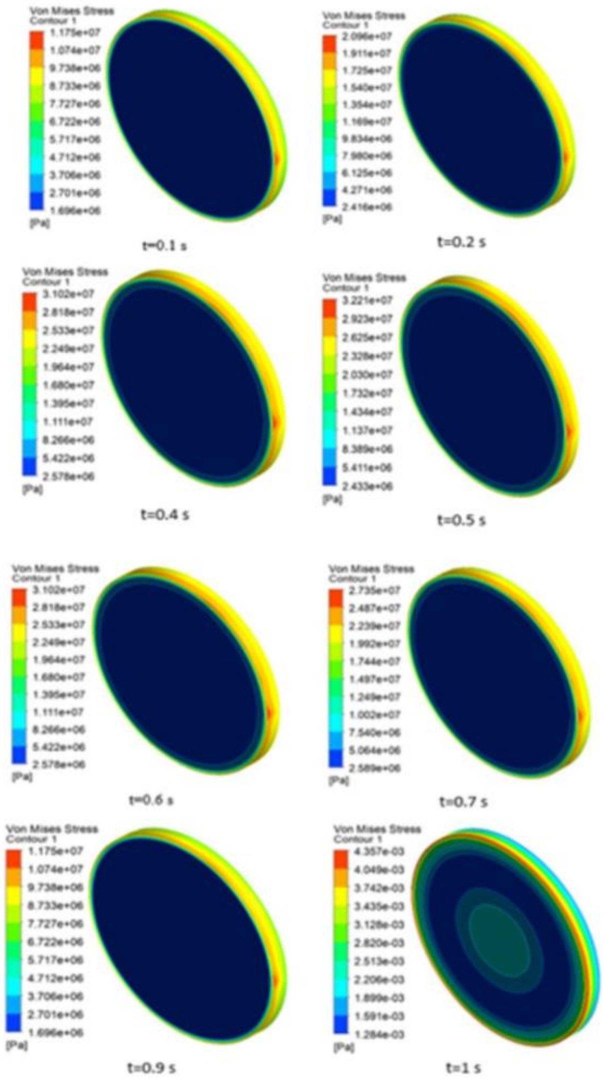

Fig. 3. Stress contours in the solid domain for the diaphragm displacement amplitude of 0.2 mm and time period of 1 s at various times from 0 s to 1 s

. The pump flow is directly proportional to the diaphragm oscillation frequency in all three diaphragm displacement amplitudes, which is consistent with such pumps' physics and observed behavior. Pump flow rate and maximum stress at the diaphragm both increase as the oscillation amplitude increases at a constant frequency. As a result, the diaphragm displacement amplitude must be carefully chosen to provide a specific flow rate, taking into account the effect of increasing the amplitude on increasing stress.

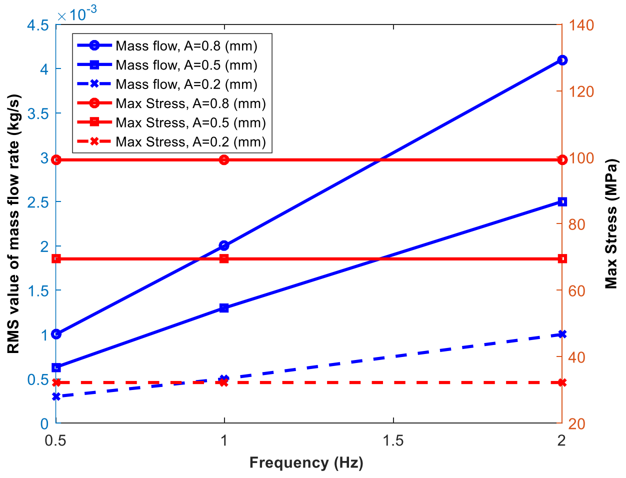

Fig. 4. RMS value of mass flow rate and maximum amount of stress at as a function of frequency for the diaphragm displacement amplitude of 0.2, 0.5 and 0.8 mm

4- Conclusions

The FSI simulation of a diaphragm dosing pump is presented in this paper. The fluid velocity and pressure distributions, fluid flow changes over time, and diaphragm stress distributions are compared and analyzed under various operating conditions. The obtained results show that as the diaphragm displacement amplitude increases, the fluid velocity, the flow rate, and the maximum stress applied to the diaphragm also increase. Furthermore, the results reveal that the pump's flow rate is proportional to the frequency of diaphragm oscillation. The applied stress on the diaphragm, on the other hand, is not frequency-dependent and is nearly constant in the same period ratios.

According to the findings, if the pump amplitude is set to 0.5 mm and the frequency is 1.6 Hz, the pump's flow rate will be the same as if the diaphragm amplitude is set to 0.8 mm and the frequency is 1 Hz. At the same time, the maximum amount of stress in the diaphragm will be lowered by around 30%. However, during pump exploitation, the diaphragm amplitude is usually set and locked at its maximum value, and the flow rate is adjusted only by changing the diaphragm's oscillation frequency. The stress on the diaphragm can be decreased by reducing its amplitude and increasing its frequency while delivering the required flow rate. Therefore, the possibility of diaphragm damage is lowered. Nevertheless, a diaphragm fatigue analysis is required for a more precise conclusion in this regard.

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HOW TO CITE THIS ARTICLE
R. Mohammadi, A. Rabiee Kerahrudi, A. Ahmadi, Numerical Modeling of Diaphragm Dosing Pumps with Fluid-Structure Interaction Analysis, Amirkabir J. Mech Eng., 54(7) (2022) 301-304.

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