Genetic programming approach for flow of steady state fluid between two eccentric spheres

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Abstract: Genetic Programming (GP) is used to estimate the functions that describe the torque and the force acting on the external sphere due to steady state motion of viscoelastic fluid between two eccentric spheres. The GP has been running based on experimental data of the torque at different eccentricities to produce torque for each target eccentricity. The angular velocity of the inner sphere and the eccentricity of the two spheres have been used as input variables to find the discovered functions. The experimental, calculated and predicted torque and forces are compared. The discovered function shows a good match to the experimental data. We find that the GP technique is a good new mechanism of determination of the force and torque of fluid in eccentric sphere model.

Keywords: Genetic Programming, eccentric spheres, steady state motion,
viscoelastic fluid

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1. Introduction

The information about the mechanical properties of solutions and melts is important for the processing of these materials in almost all branches of industries. Theoretical and experimental studies concerning the flow of viscous or viscoelastic fluids through different bodies have been discussed in [1-4]. In general, the solution of the specific boundary value problem based on microscopic models [5,6] or phemenological state equations of state [7] renders a small number of experimental measurements sufficient to determine a specific set of material parameters. The theoretical and experimental studies concerning the flow of viscous or viscoelastic fluids in the annular narrow gaps between two rotating bodies are convenient boundary value problems in rheology. For two concentric spheres such studies have been carried out, e.g., by Wimmer [8] and Yamaguchi et. al. [9,10,11]. In this case the only material parameter to be determined (the viscosity) is determined via torque measurement only. A large number of theoretical and experimental works have been devoted to the viscous flow between two eccentric spheres; cf. Jeffery [12], Stimson and Jeffery [13], Majumdar [14], Munson [15], Menguturk and Munson [16]. Recently, M.Y. El-Bakry et al. studied the flow of viscoelastic fluid between two eccentric spheres theoretically [17] and experimentally [18]. The determination of the torque and the forces on the outer stationary sphere, while the inner sphere is rotated, at different eccentricities are theoretically captured in [13], for the experimental data see [18]. For this manuscript, we have applied the Genetic programming (GP) technique in order to determine the torque and the force on the outer stationary sphere in the eccentric sphere model by using a 0.3 polyacrylamide in 50/50 glycerin/water mixture. Using Cartesian coordinates (x,y,z), the axis of rotation passes through two centers of spheres in z-direction. The two components of the force in x and y-direction therefore vanish. The remaining nonvanishing force component had been measured in [18]. The torque is obtained due to the rotation of the axis of rotation which connects to the inner sphere only by recording the angular velocity, denoted by Ω. Making use of the capability of the GP, we have estimated the function that describes the torque and the other functions that describe the force acting on the outer stationary sphere using genetic programming. The genetic programming technique has been also one of researcher's interests in modeling of different branches of physics [19,20,21].

The torque and force are highly polarizable targets. Therefore, reliable estimates of the effect of angular velocity of the inner sphere at certain values of eccentricity is rather essential to predict results for other eccentricities. The GP is fed with angular velocities and the eccentricity so that the outputs imitate the experimental data. The next section deals with the introduction and the input parameters of GP. Finally, in Section 3, we present our results and conclusion.

2. Genetic Programming representation for the torque and forces at the outer sphere in eccentric sphere model

2.1. Introduction to Genetic Programming

Genetic programming is one of a number of machine learning techniques in which the elements of possible solutions to the problem (in our case angular velocities and eccentricities) are provided to a computer program. This technique, through a feedback mechanism, attempts to discover the best solution (in our case it will be a function) to the problem at hand, based on the researchers (programmers) definition of what is called a success. The Genetic programming framework creates a program which consists of a series of linked nodes. Each node takes a number of arguments and supplies a single return value. There are two general types of nodes: functions (or operators) and terminals (variables and constants) [22]. The series of linked nodes can be represented as a tree where the leaves of the tree represent terminals and operators reside at the forks of the tree. In other words, in GP the programs are written as function which is represented in expression trees. The tree elements are called nodes. The functions (F) have one or more inputs and produce a single output value. These provide the internal nodes in expression trees. The terminals (T) represent external inputs, constants and zero argument functions. For example, Fig. 1 shows the representation of the function (A*(A+B)) i.e. *(A,+(A,B)). To read trees in this fashion, one resolves the sub-trees in a bottom-up fashion, where F = {*,+} and T = {A,B}.

The genetic programming model seeks to imitate the biological processes of evolution, treating each of these trees or programs as an “organism”. Through natural selection and reproduction over a number of generations, the fitness (i.e., how well the program solves the specific problem) of a population of organisms is improved.

A typical implementation of GP (i.e., the process of determining the best (or nearly best) solution to a problem in GP) involves the following steps:
1) GP begins with a randomly generated initial population of solutions.
2) A fitness value is assigned to each solution of the populations

3) A genetic operator is selected probabilistically.

Case i) If it is the reproduction operator, then an individual is selected (we use fitness proportion-based selection) from the current population and it is copied into the new population. Reproduction replicates the principle of natural selection and survival of the fittest.

Case ii) If it is the crossover operator, then two individuals are selected. We use tournament selection where number of individuals is taken randomly from the current population, and out of these, the best two individuals (in terms of fitness value) are chosen for the crossover operation. Then, we randomly select a sub tree from each of the selected individuals and interchange these two sub-trees. These two offspring are included in the new population. Crossover plays a vital role in the evolutionary process.

Case iii) if the selected operator is mutation, then a solution is (randomly) selected. Now; a sub-tree of the selected individual is randomly selected and replaced by a new randomly generated sub-tree. This mutated solution is allowed to survive in the new population. Mutation maintains diversity.

4) Continue step 3 for any case of the above three cases, until the new population gets solutions. This completes one generation.

5) GP will not converge. Then, step 2)-4) are repeated till a desired solution is achieved. Other–wise, terminate the GP operation after a predefined number of generations.

2.2. Genetic Programming Approach

We use the experimental data of the torque at certain values of the angular velocity of the inner sphere and the eccentricity of the two spheres to produce the torque (calculated) for each case (target atom). Also, the force at certain values of the angular velocity of the inner sphere and the eccentricity of the two spheres to produce the at certain values of the angular velocity of the inner sphere and the eccentricity of the two spheres to produce the force(calculated) for each case (eccentricity). The angular velocity and eccentricity are used as input variables to find the suitable function that describes the experimental data.

Our representation, the fitness function is calculated as a negative value of the total absolute performance error of the discovered function on the experimental data set, i.e. a lower error must correspond to a higher fitness. The total performance error can be defined for all the experimental data (j = 1 …, n) set as:

$$E = \sum_{j=1}^{n} \left| X_j - Y_j \right|^2 \qquad (1)$$

Where X_j represents the experimental data for element j and Y_j represents the calculated data for element j. The running process stops when the error E is reduced to an acceptable level (0.00001). The training data set which is used based on experimental data for the torque and force with the angular velocity at different eccentricities [18]. GP was run for 800 generations with a maximum population size of 1000. The operators (and selection probability) were: crossover with probability 0.9 and mutation with probability 0.01.

The function set is {+,-, *, \}, and the terminal set is {random constant from 0 to 10, the angular velocity, the eccentricity}. The ``full'' initialization method was used with an initial maximum depth of 27, and tournament selection with a tournament size of 8. The GP was run until the fitness function is reduced to an acceptable level (0.00001); once for each eccentricity. The discovered function has been tested to associate the input patterns to the target output patterns using the error function. The final discovered function for describing the torque, T, at the outer stationary sphere of the eccentric sphere model is given by

$$T = 315.63275 + \Omega + \frac{3118.77485}{E} - \frac{0.76705\Omega}{E} + \frac{\Omega}{E}\left(10 - \frac{E(E-10)}{0.36735}\right) \tag{2}$$

where Ω is the angular velocity of the inner sphere and E is the eccentricity of the two spheres.

The final discovered function for describing the force, F_z, at the outer stationary sphere of the eccentric sphere model is given by

$$F_z = 52.018136 + \frac{(98.2873 + 19\Omega - 3.1738E)}{0.45285 - 10\Omega} - 183.017\Omega^2 - 1000\frac{\Omega^2}{E} - 5.710\frac{\Omega}{E} + 10\Omega^2(\Omega + 1 + \frac{\Omega}{E})(1.82017E + 2\frac{E}{A}) \tag{3}$$

where

$$A = 4.9787 + 6.1191\Omega - \frac{2\Omega + 1.55825E}{\Omega - E} - \frac{10\Omega E}{2.3374 - \Omega}$$

3. Results and conclusion

Our discovered torque function (2) and force function (3) were tested using the experimental data of the torque and force using 0.3 polyacrylamide in 50/50 glycerin/water. The training data is based on experimental observations at angular velocities ranging from 10 (1/s) to 100 (1/s) [18]. The values of the eccentricities of two spheres are taken as 0, 0.2, 0.6 and 0.8 for the torque and for the force the eccentricities are, 0.2, 0.6, 0.7 and 0.8.

Figure.2 displays a good match between the experimental data of the torque at the external stationary sphere using 0.3 polyacrylamide in 50/50 glycerin/water and the calculated ones by employing our discovered function (2). After convergence, the discovered function has been used to predict torque with eccentricity 0.4, at angular velocities ranging from 10 (1/s) to 100 (1/s) which corresponds to the available experimental data [18] and Fig.3 illustrates the predicted torque compared with experimental data.
Figure.4 displays also a good match between the experimental data of the force at the external stationary sphere using 0.3 polyacrylamide in 50/50 glycerin/water and the calculated ones by employing our discovered function (3). After convergence, the discovered function has been used to predict force with eccentricity 0.4, at angular velocities ranging from 10 (1/s) to 100 (1/s) which corresponds to the available experimental data [18] and Fig. 5 illustrates the predicted force compared with experimental data.

Finally, we conclude that GP has become a relevant research area in the field of fluid mechanics. The present work presents a new technique for modelling the torque and force of the eccentric sphere model based on GP technique. The discovered function shows a good match to the experimental data for both the torque and the force. We find also that the GP technique is able to improve upon more traditional methods in different branches of physics, see e.g. Refs. [23,24,25].

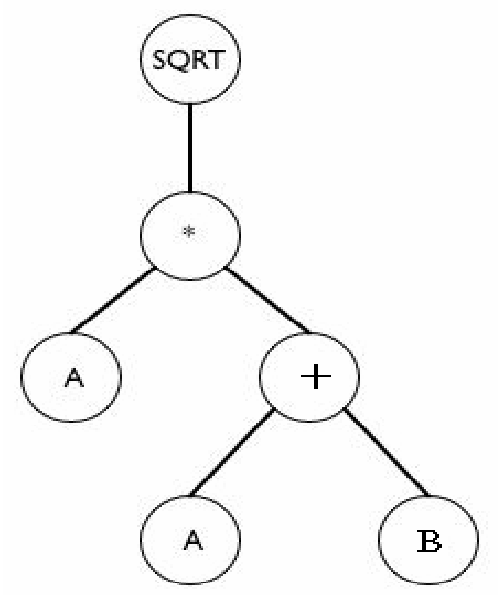

Fig (1): Tree representation of the equation square root *(A,+(A,B)) i.e. (A*(A+B)).

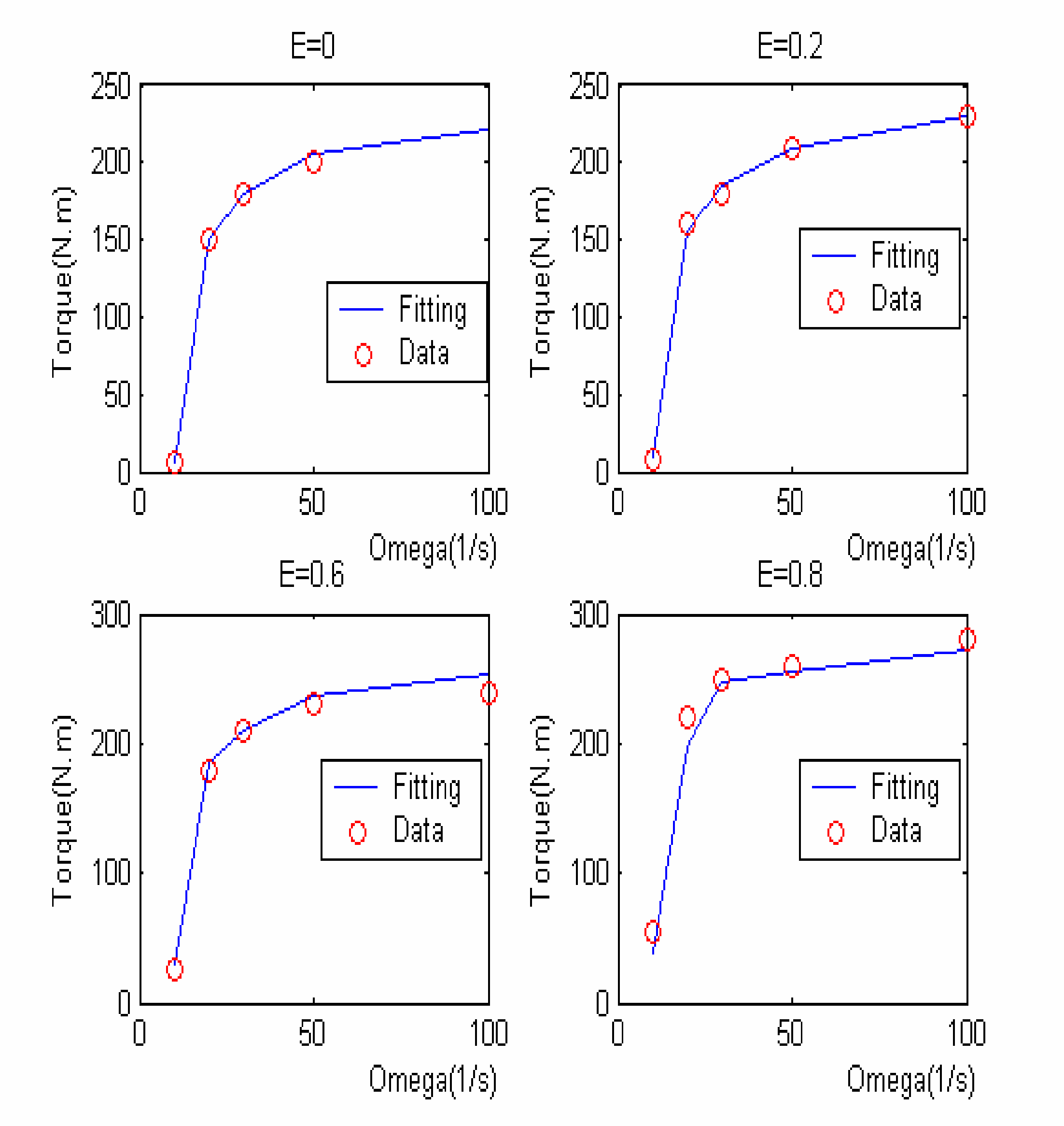

Fig. 2. Comparison between the torques (S.I. units) calculated by employing our discovered function given in (2) and the corresponding experimental points of eccentricities of 0, 0.2, 0.6, and 0.8.

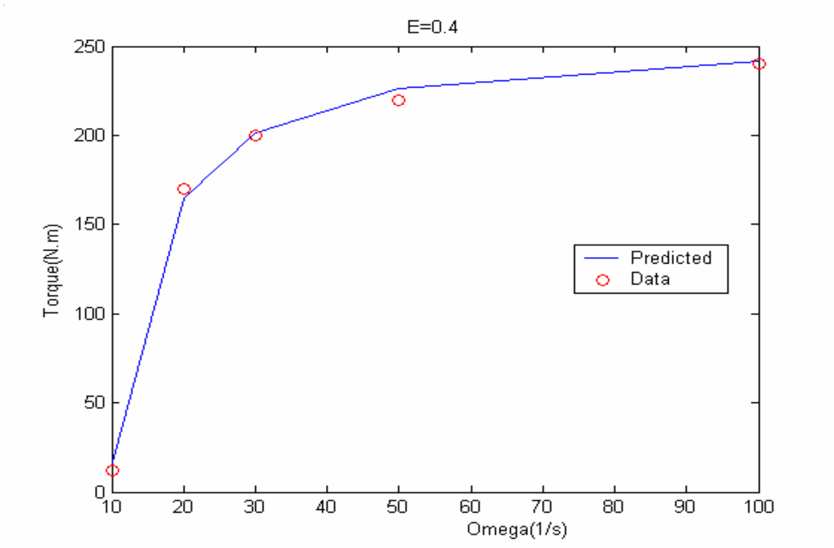

Fig. 3. Comparison between the experimental and predicted torques (S.I. units) versus angular velocity (Ω) at eccentricity 0.4.

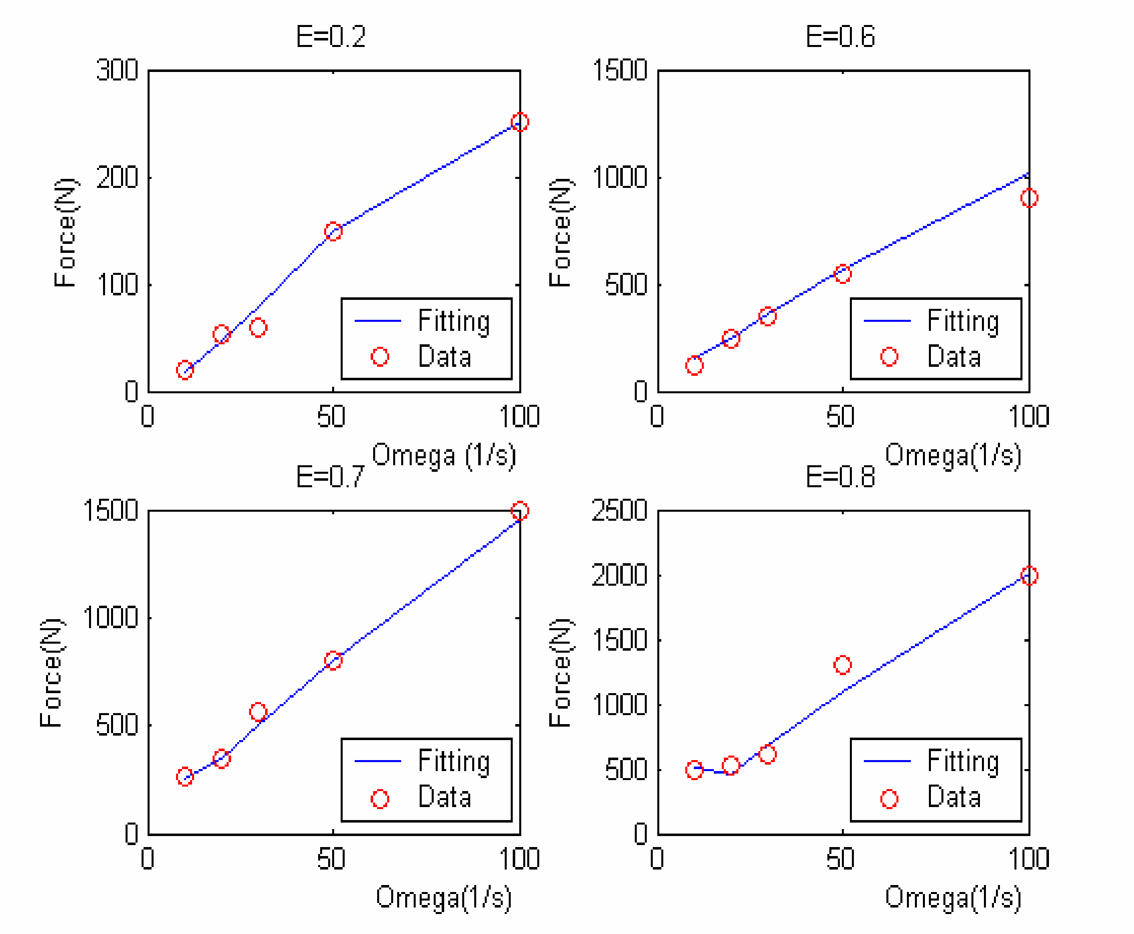

Fig. 4. Comparison between the forces (S.I. units) calculated by employing our discovered function given in (3) and the corresponding experimental points of eccentricities of 0.2, 0.6, 0.7, and 0.8.

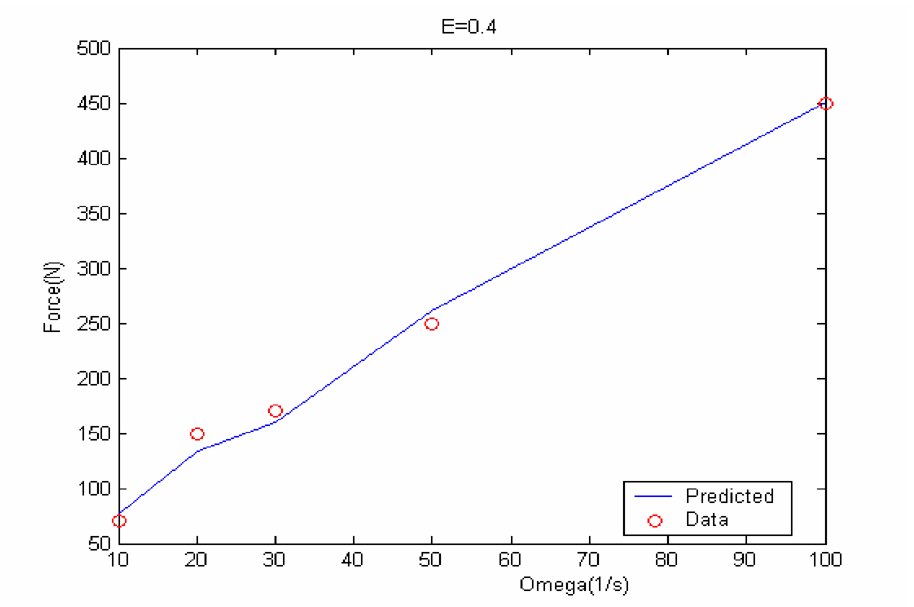

Fig. 5. Comparison between the experimental and predicted forces (S.I. units) versus angular velocity (Ω) at eccentricity 0.4.

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