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DESIGN OPTIMIZATION OF VISCOELASTIC PUMP DISCHARGE PIPE WITH NONLINEAR FINITE ELEMENT ANALYSIS

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Abstract - Viscoelastic pipes are used in hydraulic systems with the purpose of reducing vibration transmission throughout the whole system. Choosing the most suitable design and viscoelastic material is usually made by experimenting, which leads to significant amounts of time and monetary costs. In recent years, together with the development of adequate computational tools, studies started to get benefits from numerical simulations. This study presents the design optimization of viscoelastic pump discharge pipe by using nonlinear finite element analysis. The mechanical properties of viscoelastic material were obtained from DMA tests, by sweeping excitation frequencies (0.1Hz-100Hz) and material temperatures (35°C-80°C). The material master curve was fitted by using WLF shift function on MSC Marc& Mentat 2016. Neo-Hookean hyper elastic material properties and FFT results obtained from vibration measurements were used to create the finite element model. The transmitted vibration levels obtained from the experiments were compared with numerical analysis results. Finally, effect of determined geometric parameters of the pipe on transmitted vibration levels were investigated by using the numerical simulations.

Index terms - Hyperelastic materials, Neo-Hookean, Pipe Vibration, Nonlinear Finite Element Analysis

I. INTRODUCTION

Pressure fluctuations due to turbulent flows in pipelines, which conveyed from pump or the other sources, transmit vibration and noise to the elements that are connected. For this reason, noise and vibration problems in pipeline systems have been studied for many engineering applications.

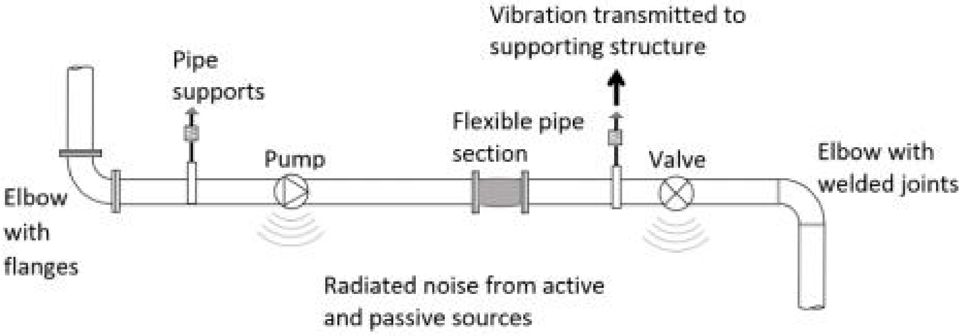

Figure 1: Airborne and structural-borne noise transmission in liquid-filled systems

In 2016, Moore [1] investigated various approaches in the literature to model the response of pipe systems. He argued that physical mechanisms that have fluid-structure interaction and vibroacoustic behavior are common to all such applications. However, he observed that the results mayvary according to the physical properties of the internal fluid or the differences in the structure of the pipe.

Another factor that complicates the modeling of piping systems is that the pump characterizes the pressure fluctuations in the fluid. Pumps are the sources of both fluid pressure stimulation and structural stimulation. Pumps cause narrow band excitation at the blade passing frequencies and broadband excitation due tothe generated turbulent flow. Rzentkowski and Zbroja [2] modeled pump as a transmission matrix and a source of pressure and volume velocity.

$$\begin{bmatrix} p_o(\omega) \\ q_o(\omega) \end{bmatrix} = \begin{bmatrix} T_{11}(\omega) & T_{12}(\omega) \\ T_{21}(\omega) & T_{22}(\omega) \end{bmatrix} \begin{bmatrix} p_i(\omega) \\ q_i(\omega) \end{bmatrix} + \begin{bmatrix} p_s(\omega) \\ q_s(\omega) \end{bmatrix}$$
(1)

Charley and Carta [3] estimated the transmission matrix of a centrifugal pump without considering the relationship between the fluid and the structure. Pavic and Chevilotte [4] presented a new method for identifying the source properties of a hydraulic pump, but reported difficulties without achieving acceptable results.

In addition to modeling the pump excitation, modeling viscoelastic materials which has non-linear behavior is also quite difficult.

Breslavsky [4] studied the effect of nonlinear vibrations on hyperelastic materials. Using rubber and biological materials, Neo-Hookean, Mooney-

Rivlin and Ogden material models have been compared with finite element software. In most cases, Mooney-Rivlin and Neo-Hookean have been found that hyperelastic materials exhibit similar static and vibration behavior. Although the best approach is the Ogden model, the cost is increasing due to the number of experiments. In this study, master curve of material was formed according to the properties of hyperelastic material measured and Neo-Hookean material model was selected. Pump excitation is provided by FFT results obtained from measurements. Main aim of this study is to minimize the transmitted vibrations and associated noise level by optimizing the design parameters of viscoelastic pump discharge pipe with nonlinear finite element analysis.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

In this study, sound power level and acoustic camera measurements were made to define the problem.DMA tests were conducted to fit material master curveand vibration measurements were made, in order to define the boundary and initial conditions for performing analyzes in MSC Marc platform.

Acoustic Measurement

Sound power level measurements were made in a semi anechoic acoustic room (SAR) in accordance with the international standards. The schematic of the experimental setup used in this study is given in Figure1.

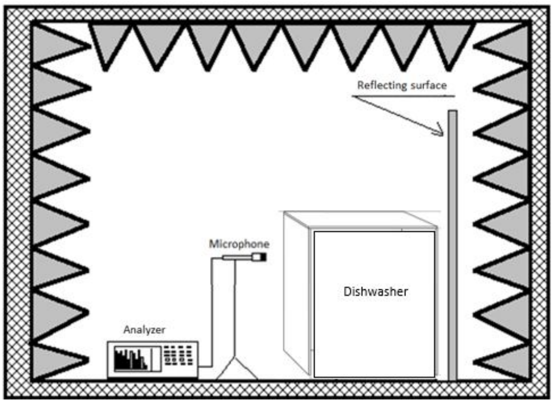

Figure 2: Schematic illustration of the sound power level measurements

As can be seen in Figure 3, which is obtained for full cycle operation of the dish washer, dominant noise levels at 100Hz and 250Hz-400Hz Octave bands are evident. In order to identify the noise sources associated with these acoustic levels, an acoustic mapping study was performed by using an acoustic camera.

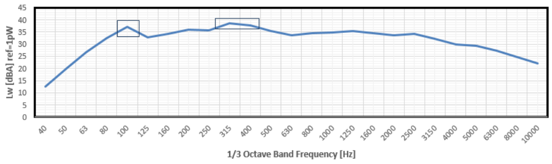

Figure 3: Spectrum of Sound Power Level of Dishwasher

Acoustic Mapping

The sound pressuremap of the region enclosing thepump system was obtained and shown in Figure 4.In 100Hz-110Hz frequency band map, it is seen that the sound pressure level increases at the electric motor operating frequency and the vibrationis transmitted over discharge pipe as noise. According to the calculations for the selected motor speed, the blade passing frequency of the pump is expected to be seen at 326.5Hz. In 270Hz-330Hz frequency band, the sound pressure mapexhibits a hotspot on sump, which has a direct connection with discharge pipe.

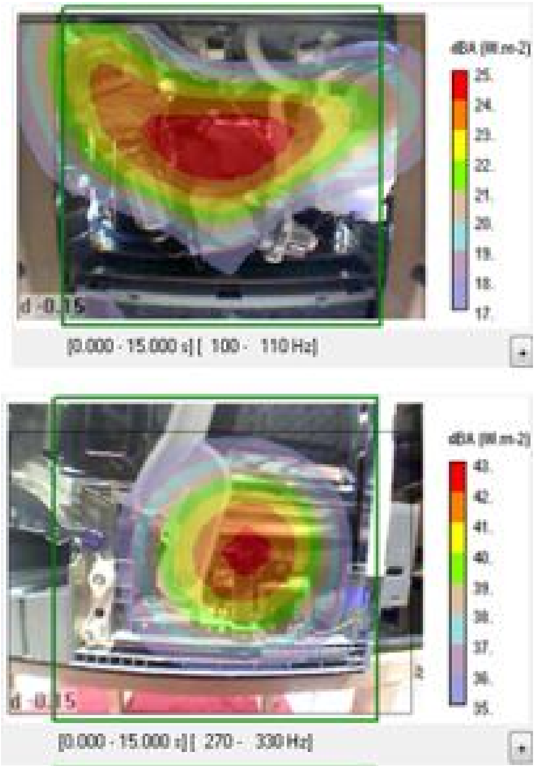

Figure 4: The map of sound pressure level ofelectric motor-pump system.

Vibration Measurement

The vibration measurements of the pipe were made with 3-axis B&K 4394 accelerometer while pre-conditioned water at a temperature of 50°C was running through the pipe. It is known that the temperature has a significant effect on the nonlinear behavior of viscoelastic pipes and by preconditioning of the water, a possible error source was eliminated.

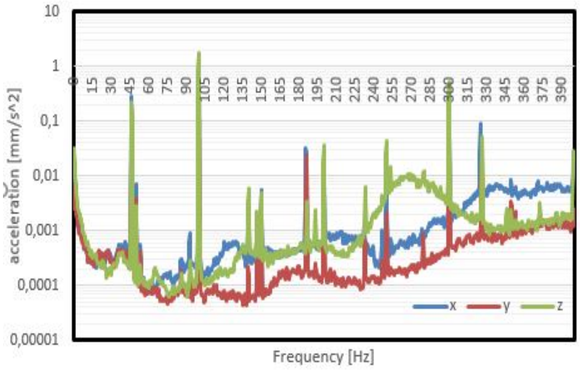

Figure 5: Vibration measurements of the viscoelastic pipe

Measurements were taken in the x-y plane, from the discharge pipe and pump connection point. In order to better simulate the flow of water, vibration measurements from various pointswere taken from the middle section of the pipe.A calculated average acceleration valuewas used in MSC Marc as harmonic acceleration on z axis for the excitation purposes.

Since 100Hz is a structural excitation frequency, it has been decided to perform verification according to this frequency. Measurements that is listed in Table 1 were taken four times from the points and error was calculated according to the RMS error.

Table 1

Number of measurements	Acceleration Amplitude$[mm/s^2]$
1st	0,274
2nd	0,290
3rd	0,287
4th	0,268

$$\mathrm{RMS}_{\mathrm{error}} = \frac{\sqrt{\sum_{i=1}^{n}(X_{\mathrm{measurement}}-X_{\mathrm{model}})^2}}{n} \qquad (2)$$

Material Characterization

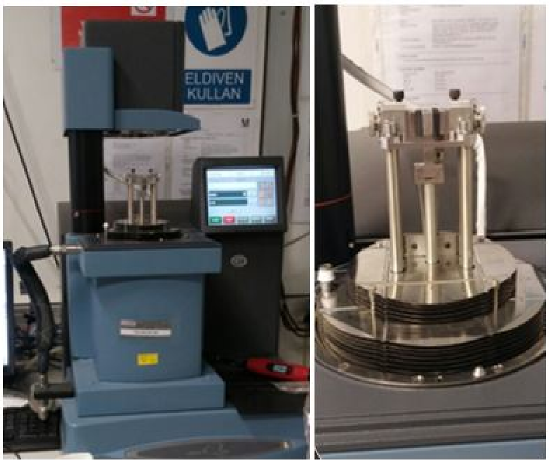

Figure 6: DMA experimental setup

The mechanical properties of the material, storage and loss modulus, were obtained by dynamic mechanical analysis with TA Instrument Q800.The six samples were taken as $1\mathrm{cm}^2$ specimens from EPDM discharge pipe. Measurements were made by sweeping frequencies from 0.1Hz to 100Hz and temperatures from 35°C to 80°C. Loss modulus and storage modulus curves of pipe are plotted in Figure 7.

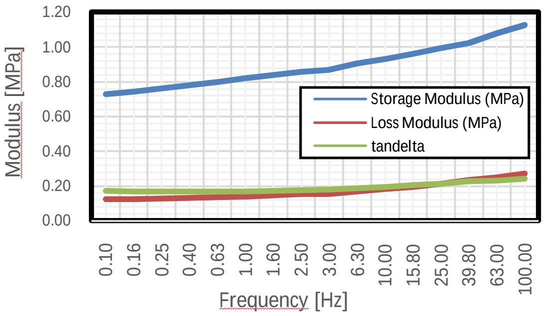

Figure 7: Loss and Storage Modulus of EPDM for 50 °C

III. NUMERICAL MODELLING AND COMPUTATIONAL SIMULATION

MSC Marc, nonlinear finite element analysis software was used in order to obtain the material master curve and acceleration amplitude of pipe - sump connection.

To fit the material master curve; storage and loss modulus datasobtained from DMA were used. After the dynamic properties of the material were given as input to the software, the experimental curve of the material is fitted by using the WLF function according to Prony series, in terms of thermorheologically simple materialat a reference temperatureof 50°C.

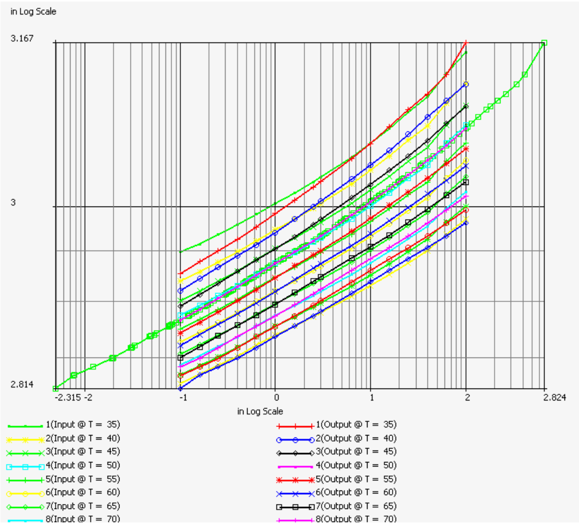

Figure 8: Experimental data fit for Storage Modulus of EPDM

As the hyperelastic material model, Neo-Hookean was selected by calculating the Mooney coefficient of the material with the short term stiffness value, which was obtained in the curve fitting parameters.It is a special case of the Mooney material type that can be used to model hyperelastic materials with high bulk modulus values.

$$W = C_{10}(I_1 - 3) \qquad (3)$$

The material is considered to be almost incompressible when the bulk modulus value is very high.For this reason, the finite element model was solved by Herrmann Formulation as 157 element type and the meshing is performed with tetra4 elements in Siemens Nx Nastran.

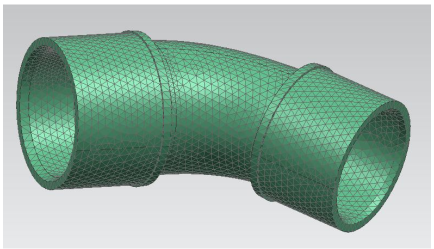

Figure 9: Mesh structure

In this study, since the fluid-solid interaction was neglected, the mass of the water was defined as the initial condition on the inner surface of the pipe. The pump dischargepressure was taken constant through the inner surface of the pipe. On pump connection side, harmonic accelerations of x-y axis were defined in the inner surface of the pipe. To simulate the fluid flow, harmonic acceleration z was defined through the inner surface. The connection of pump and sump was fixed as the last boundary condition. The RMS error which is calculated according to the results of the experimental and numerical analyses at 100Hz is below the RMS error of the experimental results as seen in Table 2. This means that the effect of parameters on this finite element model can be investigated.

Table 2

	Acceleration Amplitude[mm/ s^2]
Experimental	0,282
Numerical	0,284
RMS Error [%]	0,279
RMS Error of Experimental Measurements[%]	0,883

IV. DESIGN PARAMETERS

The parameters that affect the pipe design in terms of the vibration characteristicsand sound power levels were investigated inthe literature. In agreement with the literature, following three parameters were selected as the main concern of this study: the thickness of the pipe, the length of the pipe and the angle of the pipe, as seen in Figure 10.

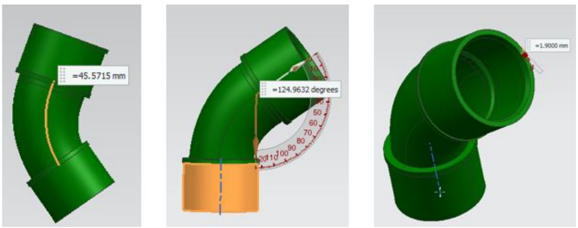

Figure 10: The length of the pipe, The angle of the pipe, The thickness of the pipe

CONCLUSION

In this study, effect of three design parameters on the vibration amplitudes were investigated numerically. The design parameters; the thickness of the pipe, the length of the pipe and the angle of the pipe were selected as the main focus points of the study. The effect of these design parameters on vibration amplitude were examined in Minitab 17.0by consideringthe results of the nonlinear finite element analysis.

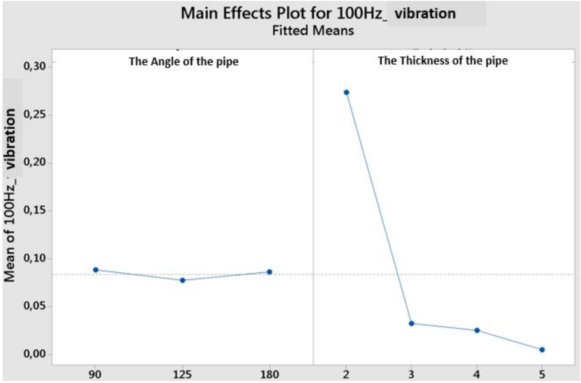

Figure 11: Effective Parameters

As seen in Figure 11, the thickness of the pipe is found to be the most effective parameter in terms of transmissibility of vibrations. Also it can be said that the length has almost no effect, compared to the thickness and the angle of the pipe.

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