# Design of a Flow Modulator to Generate Sinusoidal Pressure Oscillations

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# Design of a Flow Modulator to generate sinusoidal pressure oscillations

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## ABSTRACT

Sinusoidal pressure oscillations are of great significance for dynamic calibration of transducers, frequency response analysis, pogo studies, dynamic characterization test of pumps, etc. Basic idea of this paper is to demonstrate the generation of oscillating pressure by varying the flow area of a valve poppet, which is a direct function of the poppet position. This paper deals with design of slider crank mechanism to produce the necessary reciprocating motion of the poppet. One of the main challenges in flow modulation is to maintain the sinusoidal nature of the downstream flow oscillations. The system parameters which affect the harmonic distortion of downstream pressure is also dealt with in this text. Scope of this paper includes a lumped fluid system modelling of the flow modulator as a variable-area custom orifice with inlet and outlet pipes in MATLAB-SIMULINK. Frequency analysis of the downstream pressure is done, and the system parameters are tuned to reduce the participation of higher modes and develop near-sinusoid pressure oscillations.

**Keywords**: Flow modulator, harmonic distortion, pressure oscillation.

## 1. INTRODUCTION

Sinusoidal pressure oscillations are of great importance in a wide array of disciplines: dynamic calibration of transducers and medical devices, dynamic characterization testing of pogo suppression devices and turbopumps, frequency response analysis of systems. The background of the research arose due to requirement of flow modulator to generate sinusoidal pressure waves for dynamic characterization testing of pogo suppression devices and turbopumps. Major challenge in this field is to maintain the sinusoidal nature of the downstream pressure of the flow modulator.

## 2. LITERATURE REVIEW AND OBJECTIVE

Sinusoidal Pressure Generators (SPG) of various types and for various applications have already been developed. Many are having applications in medical fields like finding out the impedance of lungs [1] and calibrating cardiovascular catheter-manometer systems [2]. For dynamic calibration of pressure transducers, sinusoidal pressure generators have been developed operating over 10-20 kHz [3]. Some other uses of SPGs are in measuring amplitude and phase distortion in differential pressure manometers [4]. Another SPG reviewed, works on the principle of varying flow area between stator and rotating rotor lobes to generate sinusoidal pressure oscillations in mud [5].

The objective of this paper is to design a flow modulator to generate sinusoidal downstream pressure oscillations by varying the instantaneous flow area. This paper encompasses lumped fluid system modelling of the flow modulator as a variable-area custom orifice, inlet and outlet pipes in MATLAB – SIMULINK. The scope also includes frequency analysis of the simulated downstream pressure and tuning the various system parameters to generate a near-sinusoid pressure wave by suppressing the participation of higher modes.

## 3. SELECTION OF FLOW AREA PROFILE

The basic idea of the Flow Modulator is to generate oscillating downstream flow by varying the flow area. For that a system with well characterized flow area profile is required. Poppet valves are one such fluid system element whose flow area is a function of the position of its reciprocating part known as the poppet (Fig. 1).

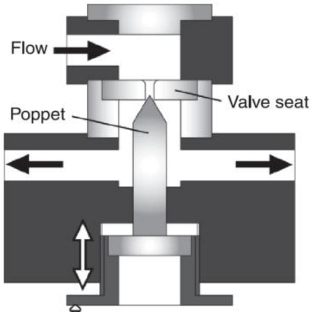

**Figure 1: Schematic of a poppet valve**

Poppet valves have many advantages such as precise control, long life due to less wear on internal seals, fast response times, and low cost. In addition, it is also used in practical applications in IC engines for valvetrain.

Instantaneous flow area of a poppet valve is dependent on its geometric parameters like seating angle and poppet diameter and the instantaneous poppet position. Hence after hardware fabrication the instantaneous flow area is solely dependent on the poppet position. Generally, poppet valve flow area has a parabolic relationship with poppet position from full-closed condition i.e., y=0.

$$A_f = ay + by^2 \tag{1}$$

## 4. PRESSURE DROP AND STROKE REQUIREMENT

To generate downstream pressure oscillation under a constant inlet pressure, the pressure drop across the flow modulator has to be oscillating. The steady state pressure drop across the flow modulator using the Discharge Coefficient method is as expressed by Eqn. 2.

$$\Delta P_{ss} = \frac{\rho Q^2}{2(C_d A_f)^2} \qquad (2)$$

Design flowrate and discharge coefficient is considered to be constant. Hence for a fixed flowrate, pressure drop is a function of only flow area, which is function of only poppet position. The required minimum and maximum poppet positions required to produce the maximum and minimum pressure drops can be computed using Eqns. (1) and (2). The assumption of the Discharge coefficient method is that, $C_d$ and Q remain constant even with varying pressure drop.

**Table 1: Analysis settings**

| | |
|---|---|
| Fluid | Liquid Water |
| Flowrate Q, l/s | 100 |
| Density of fluid ρ, kg/m$^3$ | 996 |
| Coefficient of discharge, $C_d$ | 0.84 |
| Inlet pressure $P_i$, bar | 6 |
| Required downstream pressure oscillation amplitude, bar | ≥0.5 |
| Frequency of oscillation, Hz | 30 |
| Linear coefficient, a | 0.4 |
| Non-linear coefficient, b | 1.111 |

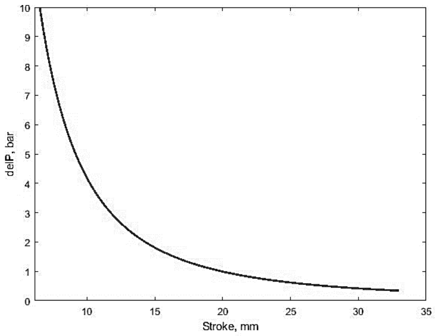

**Figure 2: Variation of pressure drop with poppet position**

Figure 2 shows the variation in pressure drop across the flow modulator, $\Delta P_{ss}$ with the poppet position, y. An important observation is that with the same poppet stroke, $\Delta P_{ss}$ variation is higher for a lower mean poppet position. This means a higher-pressure oscillation amplitude can be obtained with same poppet position by lowering the mean poppet position. One important parameter to be taken care of is the water-hammer effect which may be seen if the poppet is operating very close to the full-closed condition.

If the mean poppet position is close to the full-open condition, large strokes are required even for a small amplitude pressure oscillation. Hence the design poppet positions should be selected considering all the above factors.

**Table 2: Selected parameters**

| | |
|---|---|
| Selected max. poppet position from full closed condition ($y_{max}$), mm | 21.5 |
| Selected min. poppet position from full closed condition ($y_{min}$), mm | 13.5 |
| Min. $\Delta P_{ss}$, bar | 0.8 |
| Max. $\Delta P_{ss}$, bar | 2.2 |

## 5. DESIGN OF RECIPROCATING MECHANISM

Generally, poppet valves are used as isolation valves or on-off valves. Hence it is pneumatically actuated to open and close. But using a pneumatic actuation to continuously change the poppet position will hugely increase actuation time and will also lead to lack of precise control over the poppet position. Use of cam-follower mechanism as in I.C. engine valvetrain will require loading the valve with preloaded spring for proper return-response of the poppet in case the inlet pressure instantaneously falls. But the spring load will hugely increase the actuation force/ torque required.

Hence, another widely used mechanism in the automobile engine industry is looked into, i.e. the Slider crank mechanism. It has the capability to withstand high axial loads and has ability of huge power transmission.

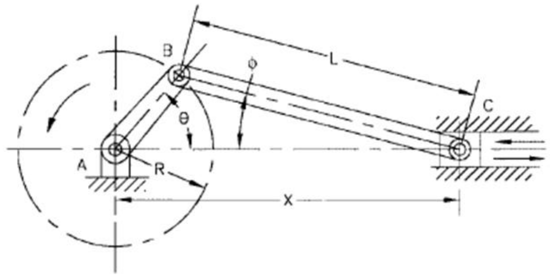

**Figure 3: Schematic of Slider crank mechanism**

Crank length is a direct function of the slider stroke (poppet travel) due to geometric constraints of the mechanism.

$$R = \frac{y_{max} - y_{min}}{2} \qquad (3)$$

Crank shaft is directly connected to the motor input shaft and undergoes full rotation. The linkage connecting the crank and the slider (poppet) is known as the connecting rod. The connecting rod does not play any role in determining the stroke, but it does play a significant role in the dynamics of flow modulator operation.

From I.C. engine literature, a thumb rule is to maintain R/L ratio much lesser than 0.5, so as to maintain smooth sliding motion, small transmission angle and minimal lateral forces.

**Table 3: Linkage dimensions**

| | |
|---|---|
| Crank length, mm | 4 |
| Connecting rod length, mm | 64 |
| Max. transmission angle, degree | 3.6 |
| R/L ratio | 0.0625 |

## 6. STEADY STATE MODEL RESULTS

A steady state mathematical model is developed for the finalised of the linkage dimensions. Inputs to the model are constant angular velocity of the motor input shaft, i.e. $\dot{\theta} = \omega$ is constant, constant inlet pressure to the flow modulator ($P_i$) and constant flowrate across the flow modulator (Q). The system of equations which takes into account the above considerations and simulates the discharge pressure as a function of time is mentioned in Eqn.s (4)-(9).

$$A_f(t) = \ ay(t) + by(t)^2 \tag{4}$$

$$\emptyset(t) = \ sin^{-1}(\frac{R}{L}.sin\,\theta\,(t)) \tag{5}$$

$$x(t) = R\,cos\,\theta(t) + L\,cos\,\emptyset(t) \tag{6}$$

$$y(t) = x(t) - (L - R) + y_{min} \tag{7}$$

$$\theta(t) = \omega.t \tag{8}$$

$$P_d(t) = P_i - \frac{\rho Q^2}{2(C_d A_f(t))^2} \tag{9}$$

The simulated poppet position and steady state pressure drop as a function of time is shown in Fig.s 4 and 5.

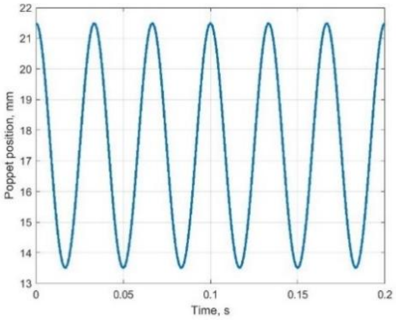

**Figure 4: Variation of poppet position with time**

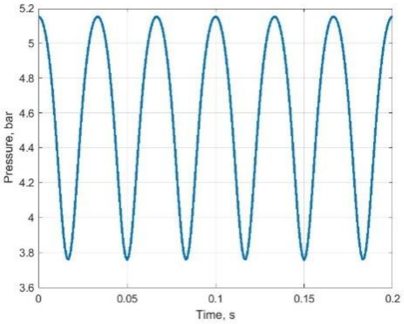

**Figure 5: Variation of downstream pressure with time**

It is evident from Fig. 5 that steady state pressure oscillations of desired amplitude are generated by the selected linkage dimensions and the poppet operating point (mean poppet position). To check the sinusoidal nature of the steady state pressure oscillation, FFT analysis is carried out and the results are depicted in Fig. 6.

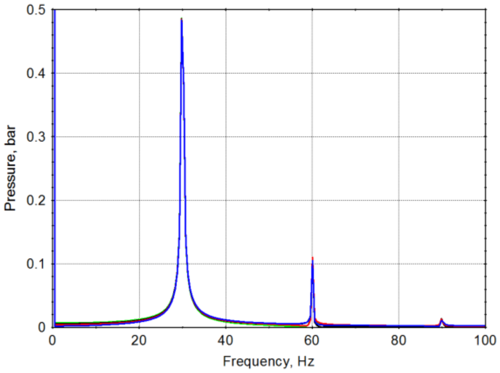

**Figure 6: FFT analysis of pressure oscillation generated**

Frequency analysis of the pressure oscillation throws light upon the participation of higher modes, although its amplitude with respect to the fundamental mode seems to be benign. One point to contemplate upon is that this non-sinusoidal nature is only due to kinematics of mechanism and flow area profile. The inertia of the fluid and the compliance of the deformable fluid systems is still not taken into account. A lumped parameter model will help to provide a closer look into the nature of the pressure oscillations generated. A schematic of Flow Modulator is shown in Fig. 7.

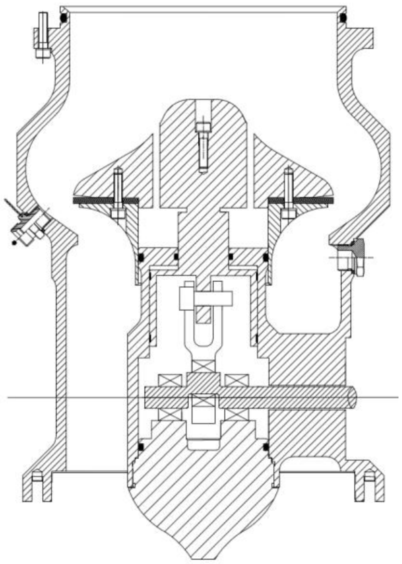

**Figure 7: Schematic of Flow Modulator**

## 7. LUMPED PARAMETER FLUID SYSTEM MODEL

The Flow Modulator setup can be modelled as an inlet pipe, a variable area custom orifice and a discharge pipe. MATLAB – Simulink provides a very interactive platform and with various pre-defined fluid elements like valves, pipes, etc. Inlet and discharge pipes are modelled as Flexible Segmented pipelines which takes into account the inertia of the fluid and compliance of the deformable pipeline. The static pressure-diameter ratio and viscoelastic time constant is computed from the pipeline geometry, material and fluid properties [6].

The Flow Modulator is modelled as a variable area orifice and does not take inertia and compliance into account. Hence the pipes become even more necessary in the setup to demonstrate the effect of inertia and compliance. A schematic of the Simulink model with standard system blocks is shown in Fig. 8.

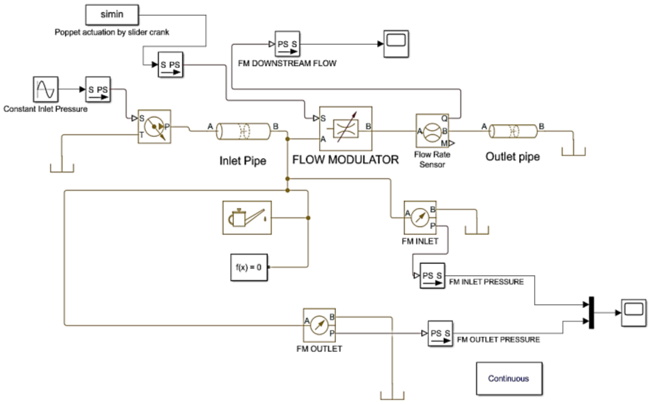

Figure 8: Simulink fluid system model

The setup is such that a constant pressure source provides the inlet pressure from t=0 to the input port of inlet pipe and the output port of the outlet pipe is connected to hydraulic reference point (atmospheric condition). The Flow Modulator block is connected between the inlet and outlet pipes. Ideal flowrate sensor is used to measure the system flowrate and two ideal pressure sensors are used to measure the flow modulator inlet and outlet pressures. Fluid used is water from the hydraulic library. Numerical solver ode23 is used for solving the model equations.

**Table 4: Model inputs**

| | |
|---|---|
| Diameter of inlet pipe, mm | 210 |
| Length of inlet pipe, m | 5 |
| Thickness of inlet pipe, mm | 4 |
| Surface roughness of inlet pipe, mm | 1e-3 |
| Diameter of outlet pipe, mm | 90 |
| Length of outlet pipe, m | 5 |
| Thickness of outlet pipe, mm | 4 |
| Surface roughness of outlet pipe, mm | 1e-3 |
| Pipe Material Yield Strength, | 200 |
| Bulk Modulus of fluid | 2.1 |

The pipe dimensions are so tuned as to obtain a mean downstream flowrate of 100 l/s through the flow modulator, same as used for steady state model. The flow area characteristics as a function of poppet position is kept the same as described in Eqn. 1 and coefficients mentioned in Table 1. The flow area characteristics are input as a two-column vector from MATLAB. Another input to the Simulink model is the piston position as a function of time actuated by slider-crank mechanism, which is also a two-column vector imported from MATLAB by solving Eqn.s (5)-(8). The constant inlet pressure is kept same as $P_i$ in Table 1. Initial conditions are: all the system elements are at atmospheric pressure and no flow through the elements.

The model is solved for 1s. The simulated upstream and downstream pressures of the flow modulator are shown in Fig. 9.

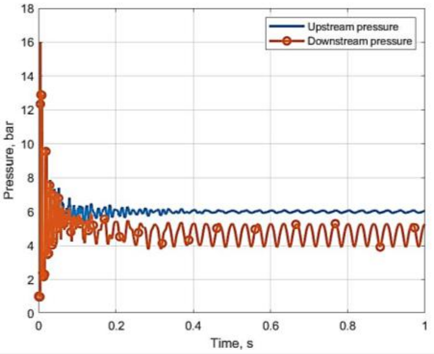

Figure 9: Upstream and downstream pressures of the flow modulator

From the simulation results it is visible that the transients die down after 0.5s and a sustained pressure oscillation of desired amplitude is generated in the downstream flow. The model results also reflect the effect of flow modulator in the upstream flow, as a steady state pressure oscillation of smaller amplitude is also seen in the upstream pressure. Figure 10 shows the simulated downstream flowrate.

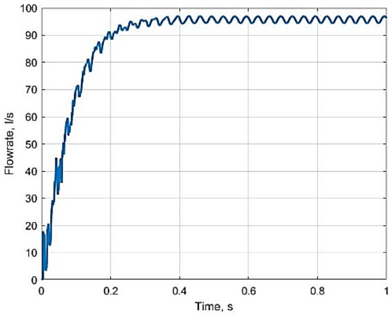

Figure 10: Simulated flowrate across flow modulator

Frequency analysis is done for the downstream pressure to check for the sinusoidal nature and the harmonic distortion of the wave (Fig. 11). Total harmonic distortion (THD) of a wave is a very good indicator of the sinusoidal nature of the wave and the percentage of participation of the higher modes with respect to the fundamental.

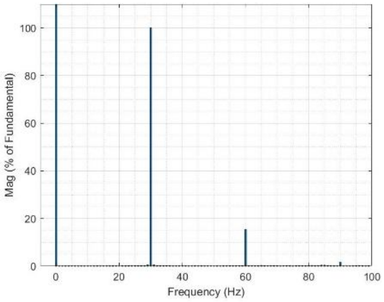

Figure 11: FFT of downstream pressure

$$THD = \frac{\sqrt{\sum_{i=2}^{n} Y_i^2}}{Y_1} * 100 \qquad (10)$$

For the current system parameters, a THD of 16% is obtained. FFT of the downstream pressure shows the participation of the higher modes. The parameters affecting the non-sinusoidal nature of the pressure oscillations are analysed in the subsequent section.

## 8. RESULTS AND DISCUSSION

In an attempt to reduce the THD of the downstream pressure oscillations while still analysing the amplitude of pressure oscillations, various system parameters are iterated. The major system parameters affecting the harmonic distortion of the pressure wave are:

- Crank length
- Connecting rod length
- Mean poppet position
- Flow area characteristics

Independent analysis of the effect of each parameter is done by iterating the parameter value and simulating the model while keeping all other parameters the same.

### 8.1 Effect of crank length

Crank length is a very important system parameter because it directly affects the stroke and hence the oscillation amplitude. The crank length is varied and the results of the iterations are displayed in Fig. 12.

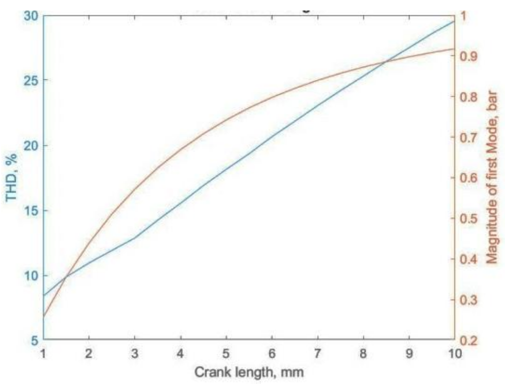

**Figure 12: Effect of crank length on harmonic distortion**

Figure 12 shows that with increase in crank length, the flow modulator is able to generate higher amplitude oscillations but the distortion also increases. The flow modulator has a capability of producing better sinusoidal waves when the amplitude requirement is lower and the crank length is lesser.

### 8.2 Effect of connecting rod length

Connecting rod length is not directly affecting the stroke nor the mean operating position of the poppet. But it affects the dynamics of the poppet motion and also the transmission angle. With respect to smoother operation and smaller transmission angle, the larger the connecting rod length, the better. To analyse the effect of connecting rod length on distortion, it is varied and the results of the iterations are displayed in Fig. 13.

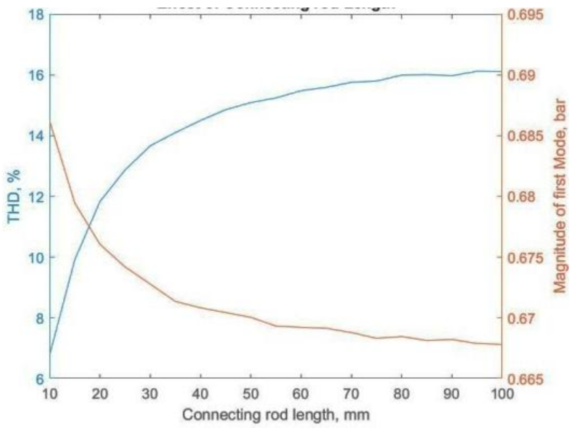

**Figure 13: Effect of connecting rod length on harmonic distortion**

There is a very clear conclusion of decreasing distortion in downstream wave by reducing the connecting rod length, while having better results in terms of amplitude. But due to hardware constraints and in order to maintain a low transmission angle for smooth operation, the connecting rod length must not be too low. To maintain smooth operation, the thumb rule of R/L ratio much lower than 0.5 must be followed.

### 8.3 Effect of mean poppet position

Mean poppet position is an independent parameter since it not only depends on the crank length and connecting rod length but also the poppet length. The mean poppet position is iterated as a variable and the results are portrayed in Fig. 14.

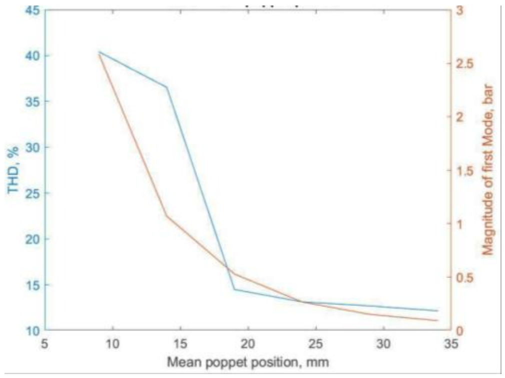

**Figure 14: Effect of mean poppet position on harmonic distortion**

Figure 14 shows that as the mean poppet position is increased i.e. the poppet operates closer to full open condition, the harmonic distortion is lesser but so is the amplitude of the pressure oscillations. So, operating close to near open condition yields smaller amplitude but near-sinusoids.

### 8.4 Effect of flow area profile

The initial considerations of the flow modulator stroke-flow area characteristics were inspired by a generic poppet valve.

Hence a parabolic relationship of flow area with respect to poppet position was assumed as described in Eqn. (1). The linear coefficient, a and the non-linear coefficient, b values considered initially are mentioned in Table 1.

An attempt was made to analyse the effect of various area profiles, keeping the maximum flow open area at full open condition to be constant. In addition, the flow area at y=0 is also considered to be zero in all cases. These above constraints lead to analysis of only one coefficient as the defining parameter of the area profile. In this instant the non-linear coefficient, b is considered as an independent parameter and the linear coefficient, a is a function of b as described in Eqn. 11

$$a = \frac{A_{fo}}{y_{fo}} - b * y_{fo} \qquad (11)$$

When $b$ is zero, the flow area is a linear function of the poppet position. When $a$ tends to zero the flow area is directly proportional to the square of the poppet position. The value of a becomes zero when value of b is $A_{fo}/y_{fo}^2$. Thus the value of b is iterated from 0 to $A_{fo}/y_{fo}^2$ and the results are displayed in Fig. 14.

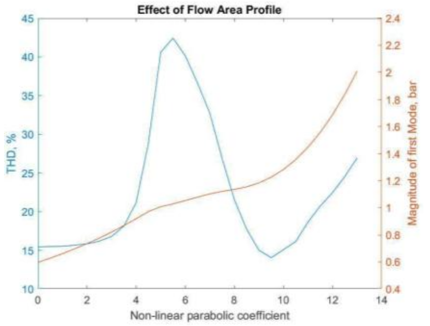

**Figure 15: Effect of flow area profile on harmonic distortion**

Figure 15 shows that when the flow area is linear or near-linear function of poppet stroke, the distortion remains constant with increase in the non-linear coefficient. However, an optimised profile with respect to harmonic distortion is possible where the THD is lowest and is even lesser than the purely linear flow area profile. The selected optimised system parameters are mentioned in Table 5.

**Table 5: Optimised parameters**

| | |
|---|---|
| Crank length, mm | 3 |
| Connecting rod length, m | 30 |
| Mean poppet position, mm | 15 |
| Non-linear parabolic coefficient, b | 9.5 |

## 9. CONCLUSIONS

A Flow Modulator with poppet-valve characteristics and actuated by slider-crank mechanism is designed. Steady state mathematical model and lumped fluid system model simulation show near-sinusoid downstream pressure generation is possible by tuning the various system parameters. For pressure waves THD of up to 10% is acceptable [3]. For the current flow modulator with the initially considered system parameters, a distortion of 16% is obtained. It is possible to dampen the harmonic distortion below 10% with the combined effect of optimised system parameters.

## ACKNOWLEDGEMENTS

We, the authors would like to thank the entire LPSC/ ISRO community for their inputs and special appreciation for the PFED team.

## NOMENCLATURE

| | | |
|---|---|---|
| $A_f$ | Flow area | [mm$^2$] |
| $a$ | Linear coefficient | [mm] |
| $b$ | Non-linear coefficient | -- |
| $y$ | Poppet position from full closed condition | [mm] |
| $Q$ | Volumetric flow rate | [l/s] |
| $\Delta P_{ss}$ | Steady state pressure drop across flow modulator | [bar] |
| $\rho$ | Liquid density | [kg/m$^3$] |
| $C_d$ | Discharge coefficient | -- |
| $R$ | Crank length | [mm] |
| $L$ | Connecting rod length | [mm] |
| $\theta$ | Angular position of crank | [rad] |
| $\emptyset$ | Transmission angle | [rad] |
| $x$ | Poppet position from motor shaft axis | [mm] |
| $t$ | Time | [s] |
| $Y_i$ | Amplitude of i-th mode | [bar] |
| $THD$ | Total Harmonic Distortion | [%] |
| $A_{fo}$ | Flow area at full open condition | [mm$^2$] |
| $y_{fo}$ | Poppet position from full closed condition to full open condition | [mm] |
| $max$ | Maximum value | -- |
| $min$ | Minimum value | -- |

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