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ON THE NONDIMENSIONALIZATION OF NOMINAL HYDRURIC CYLINDDER DYNAMICS

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Abstract. First, the special nondimensionalization of nominal hydraulic cylinder dynamics is reviewed and the nonlinear effects by the piston asymmetry are introduced. Second, the nonlinear effects by the piston asymmetry and that by the pipeline asymmetry are numerically compared with each other via the special nondimensionlization. In our numerical study, the nonlinear effects are less sensitive to the pipeline asymmetry.

Keywords: Modeling, Simulation, Control

INTRODUCTION

In comparison with electric systems, not only nonlinearity but also many physical parameters increase the difficulty in design, analysis, and control of hydraulic systems. Of course, it is well known that nondimensional representations exactly simplify the original representation with respect to the parameter space. For example, the well-known mass-damper-spring dynamics with 3 parameters (the mass, the damping, and the spring) in the original representation is exactly simplified into a new mass-damper-spring dynamics with only 1 parameter (the nondimensional damping). It is very important to develop such nondimensional representations of the nominal hydraulic cylinder dynamics as well.

In our previous works, a special nondimensional representation is developed. Unlike the usual nondimensional representation, the developed nondimensional representation preserves the physical structure, that is, the developed nondimensional representation with 10 parameters in rotation case can be equal to a special case of the original representation with only 5 parameters. However, many numerical properties of the developed nondimensionalization are not studied yet.

In this paper, asymmetry of the nominal hydraulic cylinder dynamics is numerically studied partially. First, the developed nondimensional representation is reviewed briefly. Second, with respect to the nonlinear effects in translation case, the piston area asymmetry and the pipeline length asymmetry are compared comprehensively due to our special nondimensional representation.

THE NONDIMENSIONALIZATION

Let us consider the nominal hydraulic cylinder dynamics in the original representation [1]:

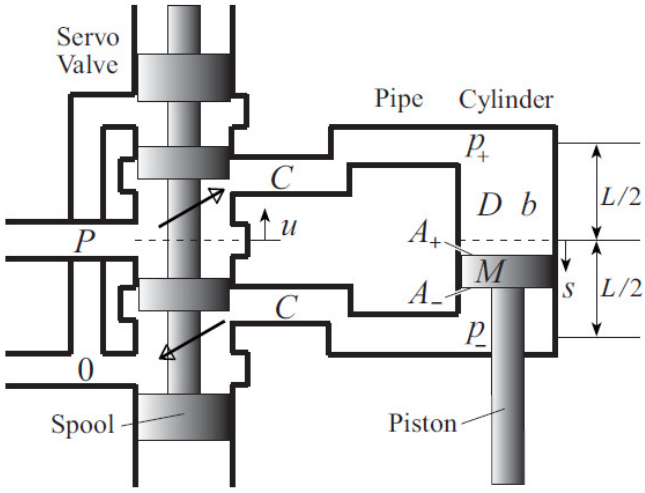

FIGURE 1. Nominal hydraulic cylinder

$$\Sigma_o \begin{cases} M\dfrac{d^2 s}{dt^2} = -D\dfrac{ds}{dt} + A_+ p_+ - A_- p_- \\ \dfrac{dp_+}{dt} = \dfrac{b}{A_+(L/2+s(t))}\left[-A_+\dfrac{ds}{dt} + Q_+(p_+,u)\right] \\ \dfrac{dp_-}{dt} = \dfrac{b}{A_-(L/2-s(t))}\left[+A_-\dfrac{ds}{dt} - Q_-(p_-,u)\right] \end{cases}$$

and

$$Q_+ = B(p_+,+u)u, \quad Q_- = B(p_-,-u)u$$

with

$$B(r,u) = \begin{cases} C\sqrt{-r+P} & (u>0) \\ 0 & (u=0) \\ C\sqrt{+r-0} & (u<0) \end{cases}$$

whose parameters are defined in Figure 1. Due to the special nondimensional representation [2][3], without loss of generality, we can assume

$$(M, A_+, L, b, C) = (1,1,1,1,1)$$

that is, the 8 dimensional parameter space is exactly simplified into the 3 dimensional parameter space in translation case. (The rotation case is skipped in this paper.)

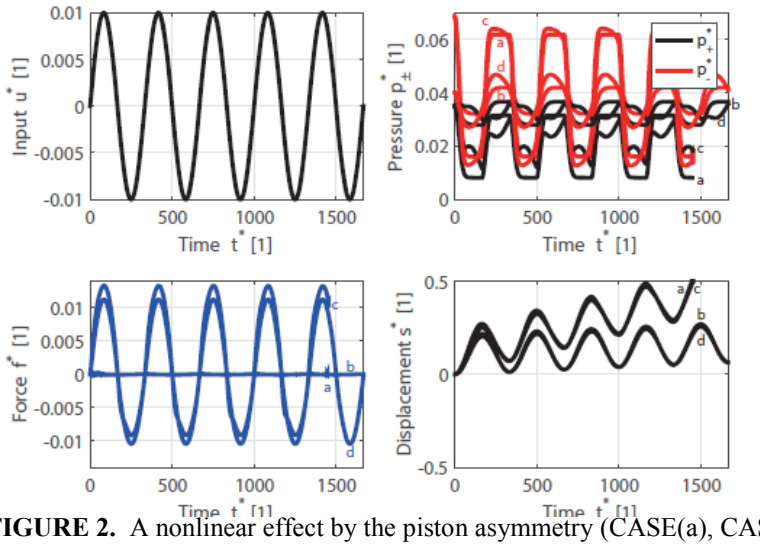

FIGURE 2. A nonlinear effect by the piston asymmetry (CASE(a), CASE(c))

Piston-Asymmetry and Pipeline-Asymmetry

Figure 2 shows that the piston asymmetry (the piston area asymmetry) generates the nonlinear behaviors by which the control performance can be lost. One may jump to think that this nonlinear behavior is caused by the nonlinear friction effects. However, this conjecture is not true. In fact, the nominal hydraulic cylinder dynamics does not have such nonlinear friction terms. If the linear approximation is applied, it is needless to say that the nonlinear piston behaviors disappear even in the presence of the piston asymmetry.

On the other hand, in many practical situations, since we can have the pipeline asymmetry (the pipeline length asymmetry), there is a possibility to design new pipelines so as to cancel or reduce the nonlinear piston behaviors coming from the piston asymmetry. In a word, it is not clarified whether a certain pipeline-asymmetry cancels or reduces the piston asymmetry or not.

In the following, let us consider the modified nominal hydraulic cylinder dynamics in the original representation:

$$
\begin{cases}
M\dfrac{d^2 s}{dt^2} = -D\dfrac{ds}{dt} + A_+ p_+ - A_- p_- \\
\dfrac{dp_+}{dt} = \dfrac{b}{A_+(L_+/2 + s(t))}\left[-A_+\dfrac{ds}{dt} + Q_+(p_+, u)\right] \\
\dfrac{dp_-}{dt} = \dfrac{b}{A_-(L_-/2 - s(t))}\left[+A_-\dfrac{ds}{dt} - Q_-(p_-, u)\right]
\end{cases}
$$

which has the pipeline asymmetry:

$$V_+(s(t)) := A_+(L_+/2 + s(t)) = A_+(L/2 + s(t)) + \bar{V}_+ \text{ and } V_-(s(t)) := A_-(L_-/2 - s(t)) = A_-(L/2 - s(t)) + \bar{V}_-$$

In this paper, with respect to the nonlinear effects, the piston area asymmetry and the pipeline length asymmetry are compared numerically. The modified backward differential formula with the variable step is applied (20-sim, Ver. 4.1, 64-bit CPU 2.60 GHz, Memory 8.0 GB). See [3] for more details.

Figure 3 shows the linearization error in the nondimensional parameter space. The color bar depicts the magnitude of the linearization error which is the output signal difference between the nondimensional transfer function (the linearized model) and the nondimensional nominal hydraulic cylinder dynamics (the nonlinear model). The vertical axis corresponds to the piston asymmetry and the two horizontal axis correspond to the nondimensional pipeline length. The same sinusoidal inputs are applied to the both models.

At any nondimensional frequency, unexpectedly, the linearization error is very sensitive to the piston asymmetry but not sensitive to the pipeline asymmetry. These results justify our previous results, that is, the nondimensional nominal hydraulic cylinder dynamics without pipeline asymmetry.

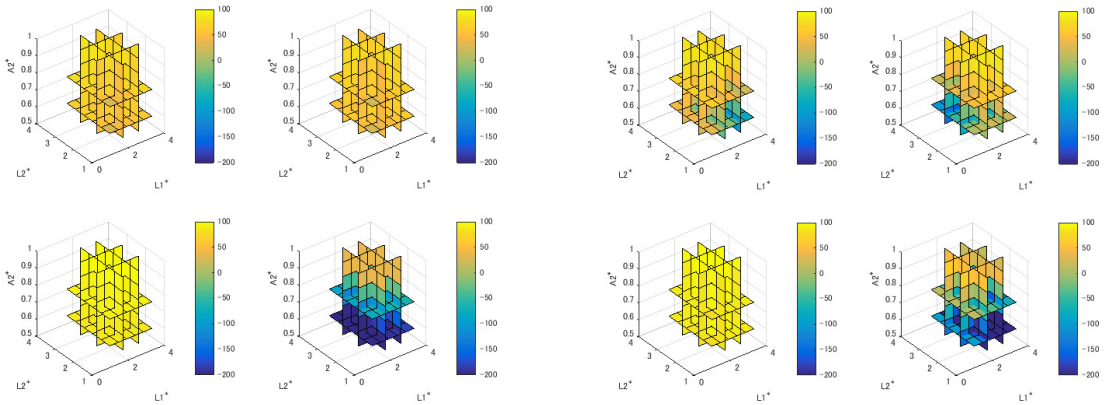

FIGURE 3. Linearization error (LEFT: Low nondimensional frequency, RIGHT: Very high nondimensional frequency).

CONCLUSION

This paper numerically studies the nonlinear effects by the piston asymmetry and that by the pipeline asymmetry. Since our nondimensional representation preserves the parametric structure of the original representation, we can study very comprehensively. . In every nondimensional frequency, the nonlinear effects by the piston asymmetry is much stronger than that by the pipeline asymmetry in this paper. These results justify the nondimensional nominal hydraulic cylinder dynamics without pipeline asymmetry, but at the same time, imply that we need not any pipeline design but some control to overcome the nonlinear behavior in Figure 2. In our next work, these results are investigated under the nondimensional damping and the nondimensional source pressure.

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