In Exploration of Unsteady Dynamics of Powered-Vacuum Fluidic Conveyance

Sun Gang, Zhang Weikang, and Alex H. LEO

Abstract—**The Powered-Vacuum Fluidic Conveyance (PVFC) consists of the fluidic conveyance switch-on process (FCSO) and the vacuum recovery phase (VR); and in turn, a FCSO is in the combination of a liquid phase and a gas phase. That is, a modularly working period is of an aggregation of liquid, gaseous and VR phases, or three events. The dynamic property of PVFC can be described in terms of time, and those phases are then mapped with a slice of time respectively. The time slices of liquid and gas phases are the major concerns in the analyzing of a dynamic property for PVFC. The method put forth in this paper is to calculate values of time slices consumed for the event-phases of PVFC. The digital simulation by the method goes along with the data of experiments perfectly.**

Index Terms—Powered-Vacuum Fluid Conveyance, Process Event, Time Slices, Analytical Method

I. Introduction

The multiphase in-pipe current is an appropriate model for Powered-Vacuum Fluidic Conveyance (PVFC). As the non-continuity and operation intermittence with abnormality and unsteadiness (A&U), neither is adequate the traditional single-phase analysis[1] to describe the behaving pattern of PVFC, nor available the popular semi-empirical[2], nor available computer-assistant[3] methods of continuous multiphase.

Having referred reference[1] describing and analyzing the current pattern and behavior of PVFC, we know a modular process is composed of an fluidic conveyance switch-on process (FCSO) and VR within a time slice; and further, the FCSO is in turn of a liquid phase and a gas phase. From this point, it is concluded that the conveyance process is a sequence of events, in liquid, gas and VR phases. With regard to the vacuum energy loss (VEL) and vacuum recovery phase (VR), a physical process of fluid conveyance is the same as the aggregation of those process events, which randomly line up in time and can be normalized in order.

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Obviously, a dynamic process of PVFC can be represented with a sequence randomly composed of the aforesaid process events. And in turn, the sequence can be normalized within a given time interval, and the events can be measured by time, if the interval as a whole is split into pieces in accordance with the length of each event. A set of random events in liquid, gas and VR phases is equivalent to, or represented as the set of the corresponding time slices.

Now it is clear that a dynamic process of PVFC with A&U is equivalent of a set of time slices of various events of solid, liquid, and VR phases, and is equal to the total length of the time slices after normalizing. As a linear algorithm is adequate in simplifying the engineering design, nonlinear methods are not necessary for the complications and difficulties. Therefore, a dynamic process of PVFC, an aggregation of the events of liquid, and gas and VRP phases, can be mapped into a random sequence of those process events, and then into a set of corresponding time slices. The event time slices come and play as a critical role in the analysis of PVFC dynamics.

II. Dynamics of Conveyance Switch-in Procedure

Along a pipe line, the loss of accumulated vacuum energy consumed by PVFC is measured through the state transitions at the set sampling points. In engineering design, however, it is popular to regard the periodicity of a PVFC in dynamics and it is required to sample a particular dynamics at many testing points along the energy-loss chain, in order to conduct energy-loss analysis. When more modules are jointed to a current pipe line system, their FCSOs may well together make the system distinct from the stable state of which only a single module is connected to the system. The dynamics of the system jointed with multi-modules is related to the event sequence of liquid, gas and VR phases, and then mapped into the sequence of the corresponding time slices. It, therefore, makes the basis for engineering design.

In a liquid phase, the fluid current in the vacuumed pipe can be simplified as the one-dimension steady motion. A typical current in the system is shown in Figure 1.

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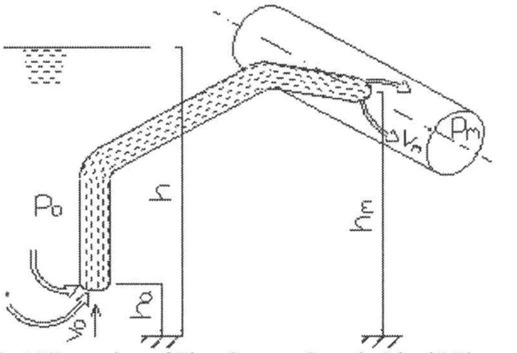

Fig.1 Illustration of Pipe Current State in Liquid Phase

For this steady current, the pressure loss is of two segments: segment I is through the liquid depth in the module, from the liquid surface of module to the position of the inlet of the connecting pipe; segment II is then from the position of the pipe inlet to that of the outlet of the pipe, vacuumed to the main pipe line.

In the segment I, the flow resistance involves in both the local loss and the fluid-in -compression-related loss at the inlet. The corresponding flow conductance to the resistance is C_i

$$C_i = C_v C_c \qquad (1)$$

where C_v for the local conductance and C_c for the compression. In segment II, the flow resistance is related to the pipe linear, the outlet dilation and the auxiliary losses. As in Figure 1, suppose p_a and v_a are the pipe pressure and flow rate at the inlet; and p_m and v_m are at the outlet respectively. If the density of the flow fluid is approximately the same, the form of D. Bernoulli equation for the pipe current from the inlet to the outlet in a liquid phase is written as:

$$\frac{p_a}{\rho g} + \frac{\alpha v_a^2}{2g} + h_a = \frac{p_m}{\rho g} + \frac{\alpha v_m^2}{2g} + h_m + h_f \quad (2)$$

where, the loss of the flow resistance is

$$h_f = \frac{\zeta_Q v_m^2}{2g} + \lambda \frac{l}{d} \cdot \frac{v_m^2}{2g} + \frac{\zeta_x}{2g} v_m^2 \quad (3)$$

Further more, the first item in equation (3) stands for the outlet dilation loss, the second the pipe linear loss, and the third the general loss of pipe connection. If along the reverse way from the outlet to the inlet, and adding up with the flow resistance of part I, formula (2) will take the form as:

$$v_m = \sqrt{2(\frac{\Delta p}{\rho} + g\Delta h)/(\alpha + \frac{\zeta_i}{C_i} + \zeta_Q + \lambda \frac{l}{d} + \zeta_x)} \quad (4)$$

where $\triangle p = p_a - p_m$, $\triangle h = h_a - h_m$, and ${}_i$ is the conversion factor. Let U_p for pressure energy and C_r for joint coefficient as fellows

$$U_p = 2(\frac{\Delta p}{\rho} + g\Delta h) \qquad (5)$$

$$C_r = 1/(\alpha + \frac{\zeta_i}{Ci} + \zeta_Q + \lambda \frac{l}{d} + \zeta_x) \quad (6)$$

With the set length, the time slice t_l comes up of the liquid phase in a FCSO event, expressed as follows

$$t_l = \frac{V_l}{A_c \sqrt{U_p C_r}} \qquad (7)$$

where V_l for the liquid volume of the liquid phase, while A_C as the across-section of the pipe.

Figure 2 demonstrates the comparison of the results from the above method and the data measured from the scene, with a perfect consistency.

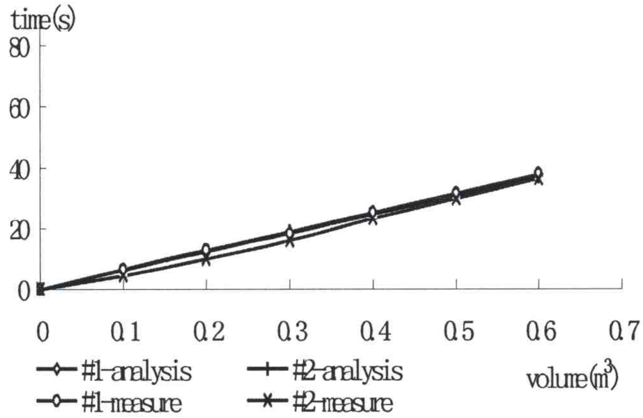

Figure 2(a) Comparison between calculation and measurement for time slices in liquid phase

It is recognized that the sequence length of multi-modules FCSOs is less or equal than that of as multitude of a single FCSO; or an increased current rate is expected in the case of multi-module FCSO in a given design interval. Therefore, the design based on in case of a single module FCSO is sufficient for the system sustainability. Figure 2(b) shows how the time-slice length of multi-module FCSOs is applicable to that of as multitude of a single module FCSO.

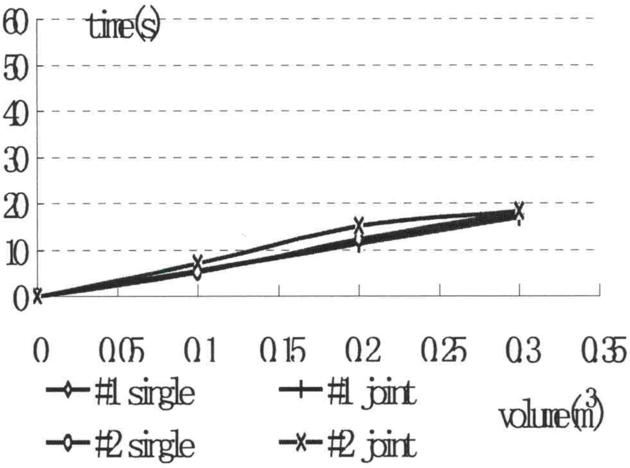

Figure2(b) Comparison of time-slice length between multi-module FCSOs and the multitude of a single module FCSO

III. Dynamics of Vacuum Recovery Procedure

The dynamic process of a long vacuum recovery can be mapped into a series of small vacuum recovery processes, corresponding to a time slice respectively.

A vacuum pipeline network has a finite space V_0, within which the accumulated vacuum energy (AVE) is proportional to V_0. As long as a vacuum recovery process long enough for restoring to the original state, the AVE in V_0 recovers from the previous losses. This process is implemented by means of

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a sequence of the VRP events or their time slices. Suppose the sucking rate of a power unit for the vacuum recovery is S_p, by means of the reducing of the air flow resistance, the effective sucking rate S_e along the main pipe is given as bellows,

$$S_e = C/(1+\frac{C}{S_p}) \qquad (8)$$

In the formula (8), C is for the flow conductance of a pipeline. The expression of flow conductance for the segment I is written as

$$C_i = \sum_i k_{i1} \frac{d_i^4 \overline{p}_i}{l_i + k_{i2} Q_{ig}} \qquad (9)$$

where d_i is the diameter, l_i the length, Q_{ig} the current of the segment, and p_i the process- average pressure, k_{i1} and k_{i2} the conversion factors.

Through the analyzing of the sequence of event time slices of VRP, assume p as the state pressure of the subspace V_0 prior to the event, and p_- the one across the event, then the event time slice length is as following

$$t = \frac{V_0}{S_e} \ln \frac{p}{p_-} \qquad (10)$$

Compared with l_i of equation (9), the item, $k_{i2}Q_{ig}$, of formula (9) is much less in contribution in most cases, so a reduced form comes as follows,

$$t = V_0 \ln \frac{p}{p_-} (\frac{l}{k_1 d^4 \overline{p}} + \frac{1}{S_p}) \qquad (11)$$

Given the subspace V_0 constant, it is worth a notice that formula (11) comes in a linear combination of formula (10), or in a chain related to individual events of the FCSO sequence. This result provides reliable analytic basis for dividing a PVFC.

Figure 3 shows the comparison of a measured and a corresponding digital simulation curves. It comes they are almost superposed.

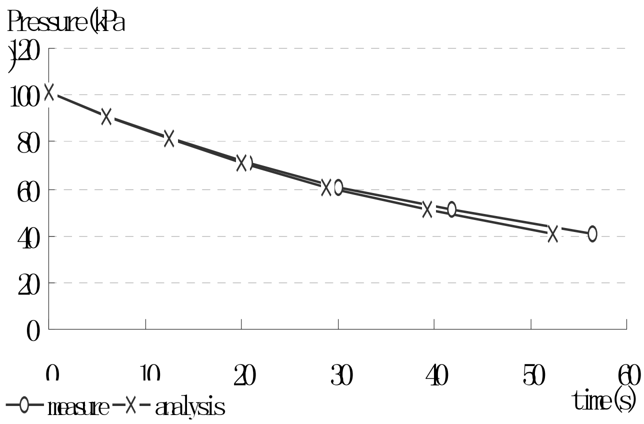

Figure.3 Comparison of measured data and simulated results of VRP time slices

IV. Conclusion

The powered-vacuum fluid conveyance is composed of a series of FCSOs and VRPs. A FCSO behaves as one liquid phase and one gas phase. The aggregation of the events of liquid, gas and VR phases is equivalent to the PVFC as a whole. The dynamic process of the conveyance is depicted by its time property. A process event is corresponding to its own time slice, and the aggregation of the process events is mapped into the set of the time slices. Based on the time property of the dynamic processes of the liquid and the VRP phases, the time-slice method is a primary fundamental to analyze and design the vacuum conveyance system, as the time-slice length of a gas phase dependents on that of the connected liquid phase and is able to be evaluated. This method is applicable for the sustainability analysis of a running system, significant for engineering design and analyses of the stability.

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