IOP Conference Series: Earth and Environmental Science

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To cite this article: Yulan Li *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1079** 012111

Variation law of pressure pulsation during variable speed operation of pumped storage units

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Abstract: Variable speed operation technology has become an emerging development direction in hydropower industry. Variable-speed pumped storage plants (VSPSPs) constantly undergo various transient processes, and ensuring the amplitude of pressure pulsation within the control range is critical to the safe operation of variable-speed pumped storage units (VSPSUs). However, its extreme value is usually determined by rule of thumb in design stage, and few researches focus on the relationship between pressure pulsation and variable speed operation of VSPSUs. In this paper, characteristic curves of pressure pulsation are plotted by processing model test results with Gridfit function, taking a real VSPSP as an example. The total pressure during transient processes is predicted by simulation of a numerical model. Load rejection conditions (change initial speed) and large load regulation conditions (change speed command and power command) are simulated, and the influence of operating trajectory on pressure pulsation during variable speed operation is analyzed. The results show that with the increase of initial speed or speed command, the value of pressure pulsation increases; the trajectory passes through more high-amplitude pressure pulsation region and gradually shifts to the S-shaped region, causing the pressure oscillation. This study could provide theoretical reference for the operation of VSPSUs.

1. Introduction

In recent years, renewable energy, such as wind and solar energy, has developed on a large scale, but the generation of these variable renewable energies is intermittent, random and volatile. Variable-speed pumped storage plant (VSPSP) has high reliability and rapidity in regulation [1-3], and it is a new development direction of pumped storage industry in the world [4]. To fulfill the functions of peak shaving, frequency regulation and emergency power supply in a power grid, pumped storage plants need to constantly undergo various transient processes. Load rejection and large load regulation under turbine mode are the main operating conditions threatening the safety of VSPSPs. At this time, the energy of water flow in overcurrent components of the unit increases and the pulsation energy increases accordingly. Under such conditions, pressure pulsation, a dynamic index, is one of the main reasons for unit vibration as well as fatigue damage of pump turbines [5, 6]. Pressure pulsation refers to the part where the pressure of each point in the flow area fluctuates in space and time due to the mixing of water particles in turbulence, and this pressure fluctuates randomly above and below a certain value. Unlike water-hammer waves caused by the rapid change of flow rate in pressurized flow conduits, the focus of this paper is high-frequency pressure pulsation. The factors causing pressure pulsation include rotorstator interaction, rotating stall and vortex rope, etc. Ensuring the amplitude of pressure pulsation within the control range is an important content to ensure the safe operation of pumped storage plants.

Existing research on pressure pulsation mainly includes theoretical analysis [7]; model test [8]; real machine test, such as drawing pressure pulsation spectrum diagram at guide vane, volute inlet and draft tube and conducting analysis with flow regime [9, 10]; numerical simulation. Compared with test measurement, numerical simulation is a more economical and fast way to study pressure pulsation, such as using SST *k-omega* turbulence model to simulate internal flow of pump-turbine and to analyze the variation law of pressure pulsation [11]. In addition to three-dimensional method, one-dimensional numerical simulation has the advantages of fast calculation speed and high flexibility, and it is also convenient to consider the influence of piping system [12-14]. However, the relationship between variable speed operation of variable-speed pumped storage units (VSPSUs) and pressure pulsation is not clear and further research is urgently required.

This paper focuses on the variation law of pressure pulsation of VSPSUs. The specific contents are as follows: In section 2, the generation method of characteristic curve of pressure pulsation and the predicting method of total pressure are introduced. In section 3, the influence of trajectory change during variable speed operation of VSPSUs on the value of pressure pulsation is analyzed. The summary is given in section 4.

2. Method

2.1. Characteristic curve of pressure pulsation

Based on the model test results of a real VSPSP, characteristic curves of pressure pulsation at volute inlet and draft tube are plotted in this section.

First, the image digitization tool is used to extract the data of test marking points in each set, including unitary speed, unitary discharge, pressure pulsation (unit: %). Then, Gridfit function in MATLAB is used to integrate, extend and interpolate the measured data of turbine model test. With unitary speed and unitary discharge as horizontal and vertical coordinates respectively, the double-amplitude contour and three-dimensional surface of pressure pulsation of VSPSUs are obtained as shown in Figure 1 and Figure 2. The data for the eight curves in Figure 2 is derived from each set of the model test. It could be observed that the pressure pulsation at volute inlet is generally slightly higher than that at draft tube.

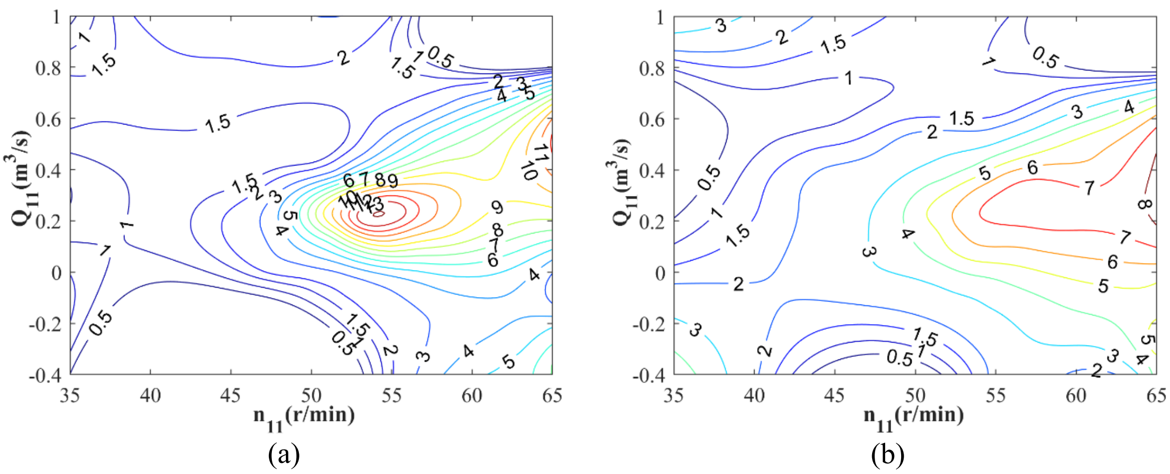

Figure 1. The double-amplitude contour of pressure pulsation: (a) volute inlet; (b) draft tube.

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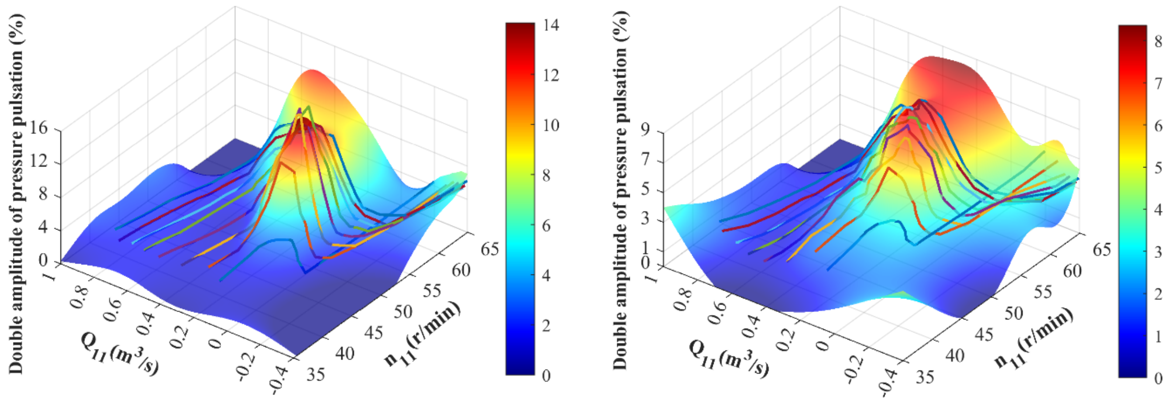


(a) (b)

Figure 2. The three-dimensional surface of pressure pulsation: (a) volute inlet; (b) draft tube.

To ensure the accuracy of fitting figures, two fitting functions (Griddata, Gridfit) in MATLAB and two fitting areas (changing the coordinate range of unitary speed) are considered. The double-amplitude difference of the value of pressure pulsation between model test and fitting under the same horizontal and vertical coordinate of the four schemes are compared as shown in Table 1.

Griddata is an effective tool for interpolation of scattered data. However, it fails when the data has many collinear points, and more convex hulls appear on the three-dimensional surface. Moreover, null values exist in corners of the fitting surface, so the sample size for error calculation becomes smaller, and its actual interpolation effect is difficult to quantify. Gridfit could solve these problems by building a surface over a complete lattice and extrapolating smoothly into the corners.

For the characteristic curves selected in this paper, the coordinate range of unitary speed is smaller. The average value of double-amplitude difference of pressure pulsation at volute inlet and draft tube is 0.065% and 0.050%, and the standard deviation of the difference is 0.084% and 0.058% respectively, and the errors are all less than 0.1%. This scheme could make the position of operating trajectory more centered on the graph, and the extreme value in corners is not too large. The data is complete and the surface is smooth without convex hulls. The interpolation fitting effect is better, and it ensures the accuracy of predicted value of pressure pulsation.

Table 1. Comparison of the four schemes (double-amplitude difference).

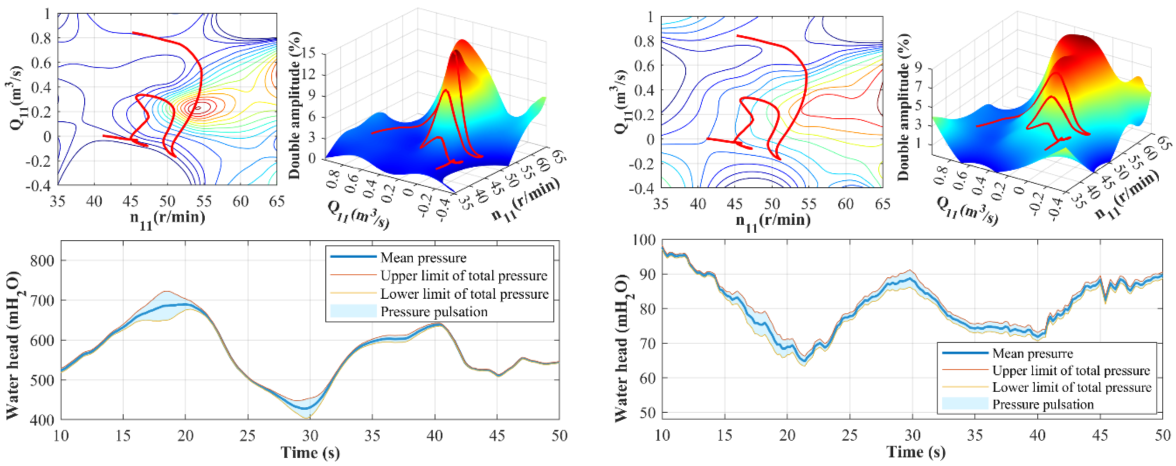
Fitting function	Coordinate range of unitary speed in fitting area	Volute inlet		Draft tube		Note
		Average value	Standard deviation	Average value	Standard deviation	
Griddata	(35, 80)	0.061	0.135	0.035	0.050	Surface is not smooth and null values exist
	(35, 65)	0.051	0.071	0.032	0.049	
Gridfit	(35, 80)	0.012	0.015	0.007	0.008	Extreme is large (>40)
	(35, 65)	**0.065**	**0.084**	**0.050**	**0.058**	Appropriate

2.2. Prediction of total pressure

The overall control strategy of VSPSU is "fast power control mode". The establishment of the numerical model relies on MATLAB / Simulink software in view of the good expansibility and flexibility of Simulink simulation module in MATLAB. The integrated model of VSPSPs with doubly-fed induction motor (DFIM) adopted in this paper is improved on the basis of the model established in literatures [15, 16].

After the operating condition is determined, mean pressure for each time at volute inlet and draft tube and the operating trajectory are obtained by running the model. Meanwhile, the value of pressure pulsation for each time is obtained in conjunction with the operating trajectory on three-dimensional surface of pressure pulsation. The total pressure could be predicted by adding mean pressure and pressure pulsation.

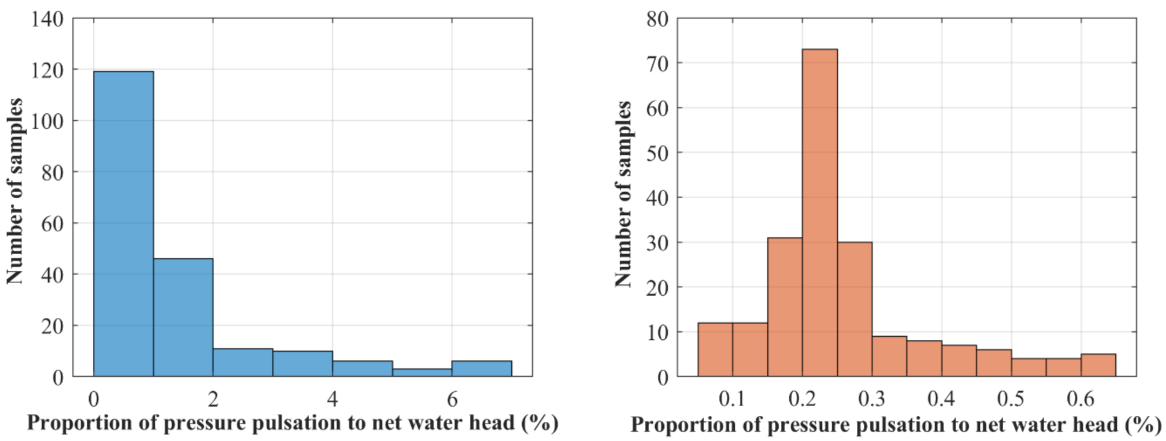
Set a load rejection condition: the initial speed of VSPSUs is the rated speed (1.0 pu); the initial guide vane opening is 0.85 pu; the guide vane closes linearly within 35 s (the 10th-45th s). The operating trajectory, predicted pressure pulsation and total pressure are shown in Figure 3. Pressure pulsation, mean pressure and total pressure reach the corresponding extreme values at similar times.



(a) (b)

Figure 3. Operating trajectory and predicted total pressure: (a) volute inlet; (b) draft tube.

In design specifications, for the maximum pressure of volute inlet, 5% ~ 7% of net water head before load rejection is usually taken as pressure pulsation margin; for the minimum pressure of draft tube, 3.5% of net water head before load rejection or 2% of net lift before a sudden pump outage is taken as the pressure pulsation margin. According to the selected load rejection condition, 200 sample points are selected in the time step of 0.2 s to calculate the proportion of pressure pulsation to net water head before load rejection, and the histogram of the proportion is shown in Figure 4. The results meet the specifications and show the accuracy of predicting pressure pulsation. Most of the sample points fall in the area with a smaller proportion of pressure pulsation, and it ensures the operational safety of VSPSUs.



(a) (b)

Figure 4. Histogram of the proportion of pressure pulsation: (a) volute inlet; (b) draft tube.

The time and value of extreme pressure are shown in Table 2. For the maximum pressure of volute inlet, the pressure pulsation and the total pressure reach the maximum value at the same time. At this time, the pressure pulsation accounts for 6.755% of net water head before load rejection. For the minimum pressure of draft tube, the mean pressure and the total pressure reach the minimum value at the same time. At this time, the pressure pulsation accounts for 0.265% of net water head before load rejection. All results are in accordance with the specifications. For the real VSPSP in this paper, the setting of pressure pulsation margin in the specifications is reasonable.

Table 2. Extreme value of pressures.

Pressure	Volute inlet			Draft tube		
	Mean pressure reaches maximum	Pressure pulsation reaches maximum	Total pressure reaches maximum	Mean pressure reaches minimum	Pressure pulsation reaches maximum	Total pressure reaches minimum
Time (s)	20	18.4	18.4	21.4	18.2	21.4
Mean pressure (m)	**689.511**	686.005	686.005	**64.757**	75.879	64.757
Pressure pulsation (m)	14.207	**36.373**	36.373	1.425	**3.358**	1.425
Total pressure (m)	703.718	722.378	**722.378**	63.333	72.521	**63.333**
Proportion of pressure pulsation (%)	2.638	**6.755**	**6.755**	**0.265**	0.624	**0.265**

3. Case study

3.1. Condition setting of load cases

The difference between fixed speed operation and variable speed operation in the variation law of pressure pulsation is analyzed in this section. The conditions are set as follows for comparison:

1) Load rejection: change initial speed; guide vane closes linearly within 35s. The initial speeds of conditions DV1, DV2, DF1, DV3 and DV4 are set to 0.92 pu, 0.96 pu, 1.0 pu, 1.04 pu and 1.08 pu respectively.

2) Large load regulation: change speed command under different active power commands. Speed command and active power command are shown in Figure 5 and Figure 6 respectively.

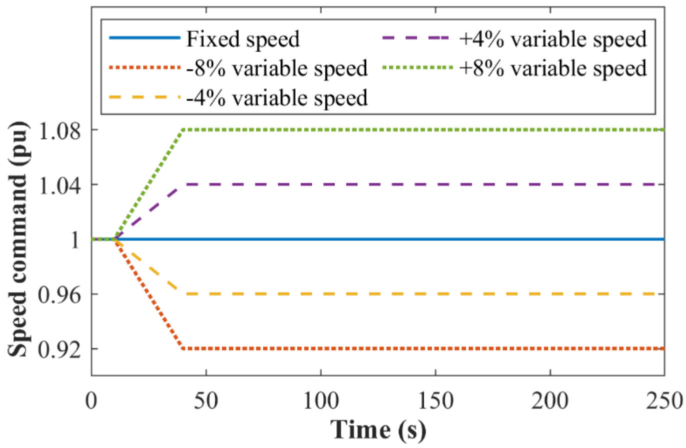


Figure 5. Chart for speed setting command.

The power command of conditions DF2 and DV5 - DV8 is to reduce (1.0 pu - 0), and the power command of conditions DF3 and DV9 - DV12 is to to increase (0 - 1.0 pu).

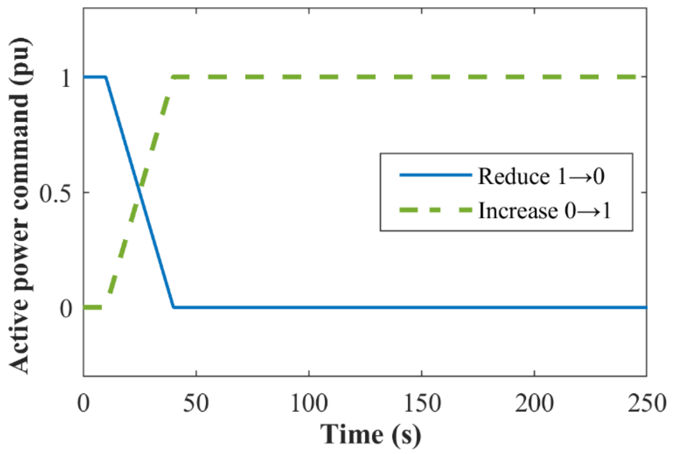


Figure 6. Chart for active power setting command.

3.2. Result analysis

For each set of operating conditions that change initial speed and speed command, the maximum value of pressure pulsation is shown in Table 3 and Table 4 respectively, and the trajectory on pressure pulsation contour figure is shown in Figure 7 and Figure 8 respectively.

Table 3. Maximum value of pressure pulsation (change initial speed; unit: m).

Initial speed	Volute inlet	Draft tube
0.92pu	33.136	3.025
0.96pu	34.968	3.191
1.00pu	36.373	3.358
1.04pu	36.582	3.422
1.08pu	36.566	3.486

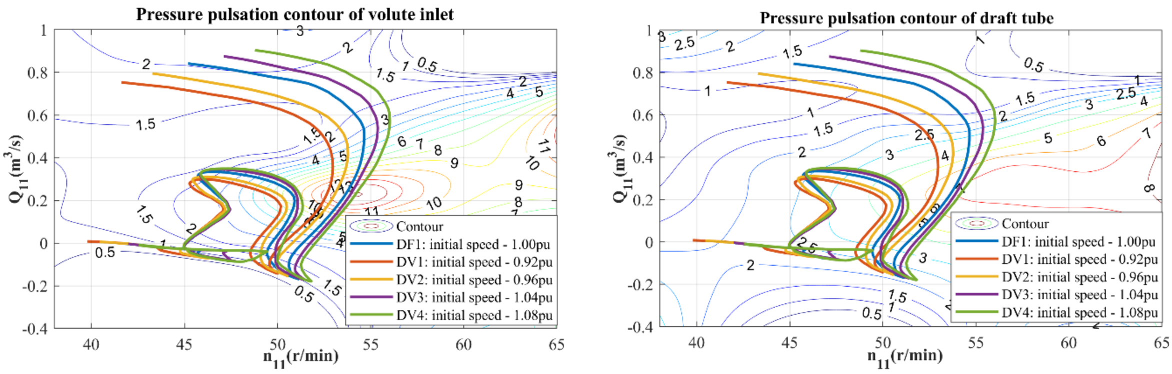


Figure 7. Evolution diagram of operating trajectory (changing initial speed).

Table 4. Maximum value of pressure pulsation (change speed command; unit: m).

Volute inlet			Draft tube		
Speed command	Active power command		Speed command	Active power command	
	Reduce	Increase		Reduce	Increase
-8%	5.325	5.515	-8%	1.204	1.212
-4%	5.362	6.364	-4%	1.231	1.297
0	6.681	6.387	0	1.364	1.311
4%	21.793	6.384	4%	2.369	1.283
8%	33.687	6.388	8%	3.128	1.311

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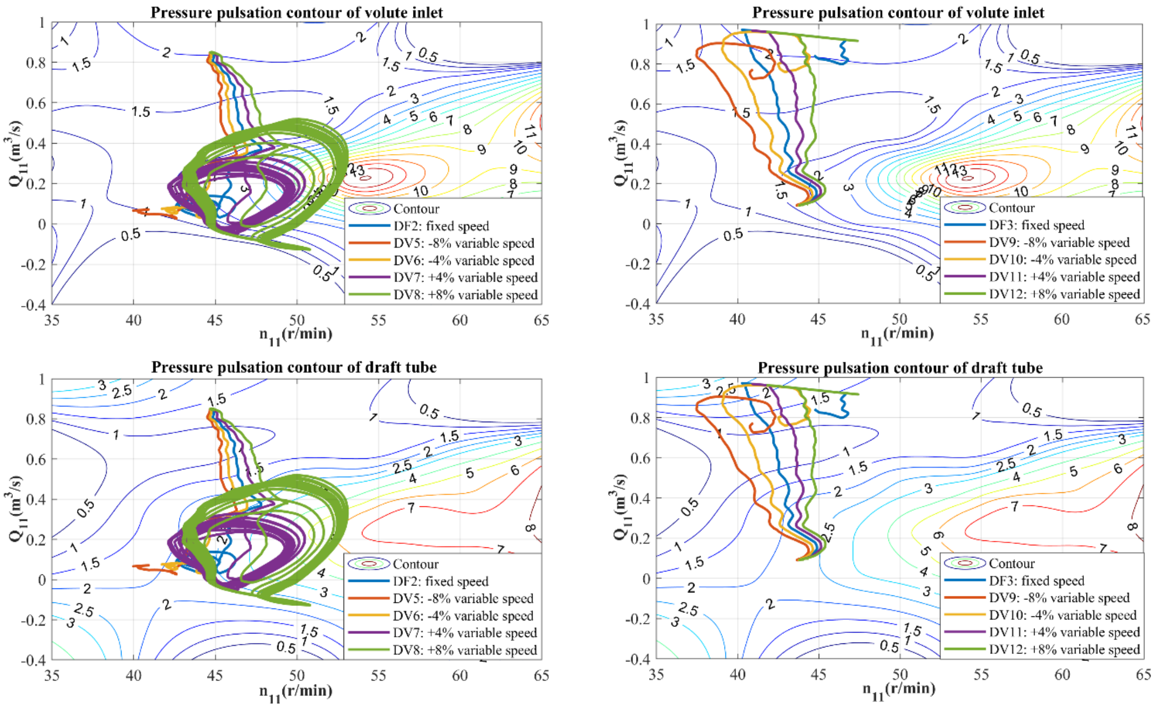


(a) (b)

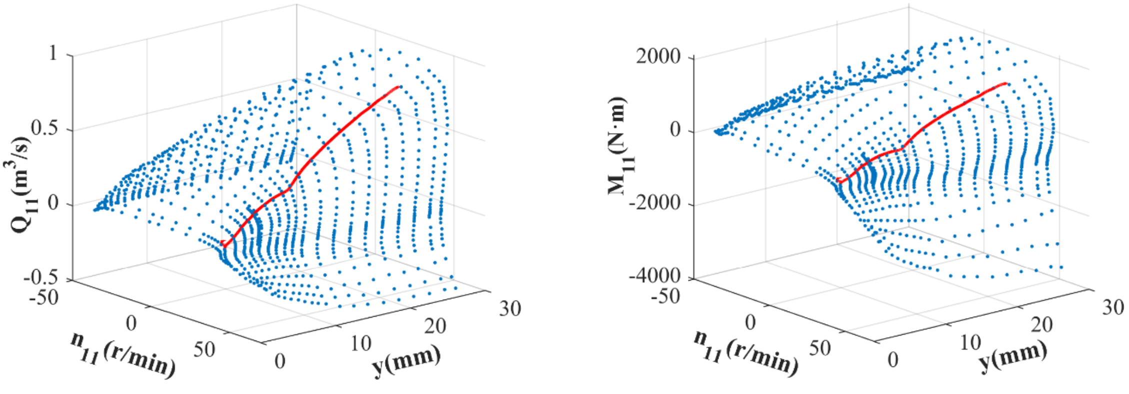
Figure 8. Evolution diagram of operating trajectory (changing speed command): active power command - (a) reduce; (b) increase.

The variation laws of pressure pulsation under variable speed operation are obtained from the simulation results as follows:

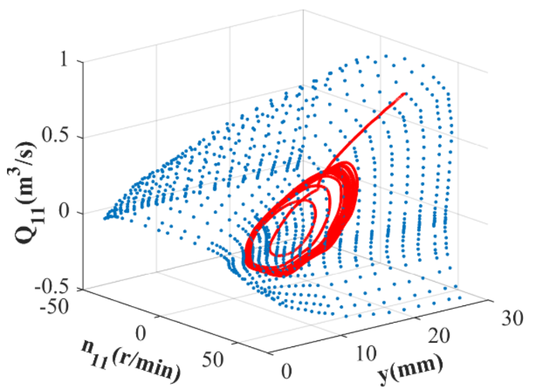
1) With the increase of initial speed, the value of pressure pulsation increases and the trajectory passes through more high-amplitude pressure pulsation region;

2) With the increase of speed command, whether the active power command reduces or increases, the value of pressure pulsation at volute inlet and draft tube is larger, and the trajectory is closer to the high-amplitude pressure pulsation region;

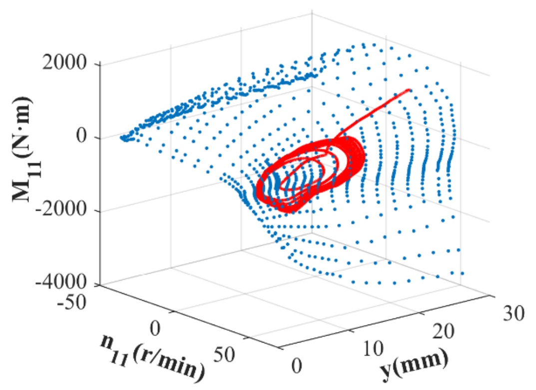
3) When active power command reduces, the trajectory changes significantly with the increase of speed command. According to Figure 9, an increased speed command would lead to the deviation of operating trajectory to the S-shaped region. The pressure at volute inlet and draft tube would oscillate seriously. It is the oscillation of physical quantities that causes the trajectory to rotate repeatedly over a wider region. A reduced speed command could prevent the trajectory from entering the S-shaped region as much as possible.



(a) (b)



(c)



(d)

Figure 9. Discharge and torque operating trajectory (reduce active power command): (a) discharge: speed command -8%; (b) torque: speed command -8%; (c) discharge: speed command +8%; (d) torque: speed command +8%.

4. Conclusion

In this paper, variation law of pressure pulsation of VSPSUs is studied. Based on the measured data of turbine model test of a real VSPSP, characteristic curves of pressure pulsation are plotted by Gridfit function in MATLAB with a good interpolation effect, including double-amplitude contour and three-dimensional surface. The method of predicting total pressure during transient process of the VSPSP by the numerical model is introduced. The proportion of pressure pulsation is in accordance with specifications, and it indicates the accuracy of predicted value of pressure. By changing the initial speed and speed command of VSPSUs, the trajectory on pressure pulsation contour figure is obtained, and the influence of trajectory change during variable speed operation on pressure pulsation is analyzed. The results show that with the increase of initial speed or speed command, the value of pressure pulsation increases; the trajectory passes through more high-amplitude pressure pulsation region and gradually shifts to the S-shaped region, causing the pressure oscillation. This conclusion provides theoretical reference for the operation of VSPSUs.

The prospect of this study is to further improve the interpolation fitting method of characteristic curves and to strengthen the engineering guidance by considering more complicated operating conditions in practice.

Acknowledgments

The authors thank the support from the National Natural Science Foundation of China (No. 52079096, No. 51879200).

References

[1] Iliev I, Trivedi C and Dahlhaug O G 2019 Variable-speed operation of Francis turbines: A review of the perspectives and challenges *Renewable and Sustainable Energy Reviews* **103** 109-21

[2] Valavi M and Nysveen A 2018 Variable-speed operation of hydropower plants: A look at the past, present, and future *IEEE Industry Applications Magazine* **24** 18-27

[3] Ciocan G D, Teller O and Czerwinski F 2012 Variable speed pump-turbines technology *University" Politehnica" of Bucharest Scientific Bulletin, Series D: Mechanical Engineering* **74** 33-42

[4] Guo T, Liu G, Yu L and Koritarov V 2013 Adjustable speed pumpedstorage hydro-generator (PSH) evaluation by PLEXOS *Energy Exemplar LLC, Oct*

[5] Xia L, Cheng Y and Cai F 2017 Pressure pulsation characteristics of a model pump-turbine operating in the S-shaped region: CFD simulations *International Journal of Fluid Machinery and Systems* **10** 287-95

[6] Widmer C, Staubli T and Ledergerber N 2011 Unstable characteristics and rotating stall in turbine brake operation of pump-turbines *Journal of Fluids Engineering* **133**
[7] Zuo Z, Liu S, Sun Y and Wu Y 2015 Pressure fluctuations in the vaneless space of High-head pump-turbines—A review *Renewable and Sustainable Energy Reviews* **41** 965-74
[8] Yamamoto K, Müller A, Favrel A, Landry C and Avellan F 2014 Pressure measurements and high speed visualizations of the cavitation phenomena at deep part load condition in a Francis turbine. In: *IOP Conference Series: Earth and Environmental Science*: IOP Publishing, p 022011
[9] Yang J, Hu J, Zeng W and Yang J 2016 Pressure pulsation during transition of prototype mixed flow pump turbine *Journal of Hydraulic Engineering* **47** 858-64 [In Chinese]
[10] Trivedi C, Cervantes M J, Gandhi B and Dahlhaug O G 2014 Transient pressure measurements on a high head model Francis turbine during emergency shutdown, total load rejection, and runaway *Journal of Fluids Engineering* **136**
[11] Qian Z, Lu J, Guo Z and Zhang J 2016 Characteristics of pressure pulsation in pump-turbine under turbine mode *Journal of Drainage and Irrigation Machinery Engineering* **34** 672-8 [In Chinese]
[12] Alligne S, Nicolet C, Tsujimoto Y and Avellan F 2014 Cavitation surge modelling in Francis turbine draft tube *Journal of Hydraulic Research* **52** 399-411
[13] Yang J, Yang J, Wang C and Bao H 2014 Simulation of pressure pulsation of a pump turbine in load rejection *Shuili Fadian Xuebao/Journal of Hydroelectric Engineering* **33** 286-94 [In Chinese]
[14] Ye J, Zeng W, Zhao Z, Yang J and Yang J 2020 Optimization of Pump Turbine Closing Operation to Minimize Water Hammer and Pulsating Pressures During Load Rejection *Energies* **13** 1000
[15] Yang W and Yang J 2019 Advantage of variable-speed pumped storage plants for mitigating wind power variations: Integrated modelling and performance assessment *Applied Energy* **237** 720-32
[16] Huang Y, Yang W, Zhao Z, Yang J, Li Y, Ma W and Yang J 2021 Nonlinear simulation of speed variation of variable-speed unit under large disturbance by Simulink. In: *IOP Conference Series: Earth and Environmental Science*: IOP Publishing, p 012140