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Comparison of initial accumulator design using analytical and numerical methods

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Summary

Accumulators are used in order to reduce the pressure pulsations generated by reciprocating pumps. The design of such an accumulator is often done using an analytical sizing method at the start of the project. Depending on the system, the effectiveness of the accumulator on dampening the pulsations for a given system can be verified using an elaborate pulsation study according to the API 674 design code in the later stages of the project. For other systems, the actual operation of the system is used to prove the correct accumulator design. This approach is almost trial-and-error as the analytical method used for the initial sizing of the accumulator can have significant short comings as will be shown in this paper. Improper accumulator design in the initial stages of a project can lead to costly system changes later on in the project, either by having to completely change the accumulator design, or in the adding and strengthening pipe supports.
A comparison is made here between the analytical design method and a computational design method. The major characteristics of an accumulator are described using the computational method. The results show that the analytical method should be used with caution when designing an accumulator and predicted pulsation levels can be significantly different from the actual pulsation levels. The results also verify an existing guideline of placing the accumulator as close to the pump as possible.
The computational design method as described in this paper can be used by OEM’s of pumps and accumulators as an alternative to the analytical sizing method allowing for a more robust initial design of the pump and accumulator configuration at the start of a project, reducing cost at a later stage of the project.

Introduction

Accumulators as defined in this paper refer to any type of pulsation dampening device using a gas volume in order to dampen pulsations generated by reciprocating pumps. Accumulators go by several different names in industry such as pulsations dampeners, shock absorbers and flow stabilizers. The design and sizing of these types of devices is often left the OEM's of either the accumulator or the pump (skid). Accumulator design usually occurs at the start of a project and in several cases the analytical method as described in this paper is used in order to size the accumulator. For many projects, no additional calculations are done during the design of the system, and operation in the field proves whether the accumulator is correctly designed for the system. However, the final level of pulsation in a system is a combination of the effectiveness of the accumulator for a certain pump as well as the level of resonance occurring in the piping connected to the pump. For critical systems, an elaborate pulsation study according to the API 674 can be conducted in order to predict the final pulsation level taking into account the complete system. These pulsation studies are expensive and time costly and can result in even more costly last minute changes to the system as the pulsation studies can only be conducted at the final stages of the system design when the piping routing is known. In this paper, an additional design method is proposed using computational methods capable of designing an accumulator at the start of a project without knowing the exact routing of the downstream piping. Using this method one can create a more robust accumulator design then with existing analytical methods. This will result in a significant higher chance that pulsations remain within acceptable limits regardless of the exact routing of the connecting piping. This can significantly reduce the risk of costly last minute design changes.

Goal of accumulator design

Accumulators are implemented in a system in order to reduce the pressure pulsations in the system generated by reciprocating pumps. High level of pressure pulsations are unwanted and can cause the following:

- Shaking forces (leading to mechanical failure),
- Reduced pump valve life,
- Noise.

Depending on the mechanical design of the system, shaking forces can cause pipe vibrations and eventually mechanical failure due to fatigue. Prevention of fatigue failure due to pressure pulsations is therefore the main goal when reducing pressure pulsations.

The pulsation level in a system depends not only on the accumulator but also on the pump type/design, and the geometry of the complete piping system. The pump is the initial source of excitation, the main purpose of an accumulator is to reduce the excitation from the pump, and the overall piping geometry determines whether the pump pulsations are either amplified or further dampened (through acoustical resonance). Acoustical resonance depends on the frequency of the pulsations as well as the acoustical lengths contained in the system. Each system contains different natural frequencies at which resonance can occur. In summary the following aspects determine the level of pulsations in a system:

- Pump design (source of excitation),
- Accumulator design (reduces source excitation),
- Overall piping geometry (acoustical resonance of excitation produced by the accumulator/pump combination).

The final pulsation level can be predicted by modelling and simulating the complete pump, accumulator and piping geometry using computational software. Currently, two methods in order to predict the final pulsation levels are commonly used:

1. Initial accumulator design using the analytical method
2. Conducting a pulsation study after initial design of complete system.

In the situation for which the piping geometry is not known yet or a complete pulsation analysis is too costly, an accumulator should be designed in a robust way in order to prevent high pulsation levels regardless of the connecting piping geometry. The goal of any initial accumulator design should therefore be to reduce the initial source excitation for all frequencies contained in the initial source to a lowest possible level.

A new design method is proposed which offers more robust initial design of the accumulator. The method can be used to optimize the accumulator performance at given frequencies depending on the pump type and design. The proposed design method uses a model of the pump and accumulator together with anechoic boundary condition for the connected piping to the pump skid. Computational tools are used to calculate the effectiveness of the accumulator at all frequencies of interest and can predict the initial pulsation levels of the pump/accumulator configuration. A ratio of the initial predicted pulsation level and the API 674 limit can be used as a safety margin against possible resonance in the system. Larger ratios offer a more robust system in which pulsation levels remain within the API 674 limit even if amplification occurs due to resonance in/with the connecting piping.

Analytical sizing method

A typical sizing rule used by OEM's is based on combining the estimated fluctuating fluid volume generate by a pump with the equation of the ideal gas law. The goal of the analytical sizing method is to determine the minimum gas volume required to reduce the maximum pulsation level to a prescribed percentage of the mean line pressure.

The analytical sizing method depends on a description of the pump in order to calculate the fluctuation volume per stroke as well as the final required pulsation level as percentage of the line pressure. The input parameters include number of cylinders, displaced fluid per stroke of a single cylinder, pump speed, line pressure, pump coefficient, required peak-to-peak pulsation level after accumulator. Based on these parameters the analytical method prescribes a minimum required gas volume for the accumulator in order to sufficiently reduce the pressure pulsations. Sometimes, the final sizing of the accumulator is supplemented with several recommendations regarding the geometric positioning of the accumulator e.g. minimizing the distance between the pump and accumulator. The minimum required gas volume is calculated based on the analytical method using:

$$V_o = \frac{\Delta V}{\left(\frac{P_o}{P_1}\right)^{\frac{1}{n}} - \left(\frac{P_o}{P_2}\right)^{\frac{1}{n}}} = \frac{\delta \cdot \frac{\pi \cdot d_p^2}{4} \cdot l_p}{\left(\frac{P_o}{P_1}\right)^{\frac{1}{n}} - \left(\frac{P_o}{P_2}\right)^{\frac{1}{n}}}$$

where δ is a non-dimensional pump coefficient, d_p is the piston diameter [dm], and l_p is the piston stroke length [dm], V_o is the minimum required volume at charge pressure [L], n is the polytropic expansion coefficient [-], P_o is the line pressure [bar], P_1 and P_2 are the minimum and maximum fluid pressure [bar] due to the fluid fluctuation, respectively. The pump coefficient is used to correct for flow effects which can reduce the actual fluid fluctuation. The most notable effect is that of the overlap of two or more cylinders during the discharge phase. Typical pump coefficients range between the 0.6 for simplex pumps up to 0.05 for quintuplex pumps. The polytropic expansion coefficient can range from 1.0 for an isothermal process to 1.4 for an adiabatic process. In reality, the values of n is somewhere in between but most often a value of 1.4 is used. This value is also used in this paper. The accumulator is typically charged at a lower pressure then the actual line pressure in order to prevent over-expansion of the bladder for example. In this paper a charging pressure of 0.8 times the line pressure is used. If the operating temperature of the system differs from the charging temperature, the charging pressure should be corrected for.

Computational method using BOSpulse

The simulation of pressure pulsations through piping systems can be done using specialized software packages. These packages use some discretization of the one dimensional flow equation as described in for example Wylie et al. (1993). The software package used in this paper is the commercially available package BOSpulse 1.1 which solves the one dimensional wave equation in the time domain using the method-of-characteristics (MOC). The time domain results are then converted to the frequency domain in order to determine the amplitude of the pulsations per frequency. Using a computation approach, the accumulator can be design in much more detail taking into account the full geometry of the pump and accumulator configuration, more detailed pump characteristics as well as a pulsation level per frequency. If the routing of connecting piping downstream of the accumulator is not known yet, an anechoic boundary condition can be placed at the connecting end. This boundary condition does not reflect any pressure waves and represents an infinite long

piping system. The output of the analysis is a frequency spectrum, which can be compared to API 674 allowables.
The pulsation software used in this paper has successfully been used for pulsation analysis purposes for several decades now and can better capture the actual physics than the analytical method. The results using the computational method are therefore assumed to be closer to the actual pulsation level observed than those predicted using the analytical method.

Description of two test cases

This paper focuses on the effectiveness of the accumulator to dampen the initial excitation source of pulsations given different design parameters using two different methods. Also, a comparison is given in the predicted pulsation level using the analytical method and the computational method.

Table 1 | Overview parameters used for test cases.

	unit	*Triplex*	*Quintuplex*
Number of cylinders	[-]	3	4
Piston Area	[m^2]	0.0025	0.0025
Piston stroke length	[mm]	120	120
Con rod length	[mm]	300	300
RPM	[-]	300	300
Flow @ rpm	[m^3/hr]	16.2	27
Operating temperature	[degC]	60	60
Line Pressure	[barg]	120	120
Ratio charging pressure	[-]	0.8	0.8
piping internal diameter	[mm]	43	65

For the purpose of comparison the connecting piping is initially ignored. Two cases are studied representing two typical pump accumulator configurations. The two test cases include a triplex and a quintuplex pump. The parameter details for each test case are shown in *Table 1*. Many different types of accumulators exist, e.g. branch connected or in-line. The accumulator type studied in this paper is of a bladder type connected to the main header through a Tee connection. The test cases are only set-up for the discharge side of the pumps. However, as the magnitude of the pressure pulsations (in general) is independent of the line pressure, the results for the discharge side in terms of accumulator design are also applicable for the suction side of the pump. In the remainder of the paper the terms upstream and downstream of the accumulator will refer to the piping between the pump and accumulator and the connecting piping, respectively.

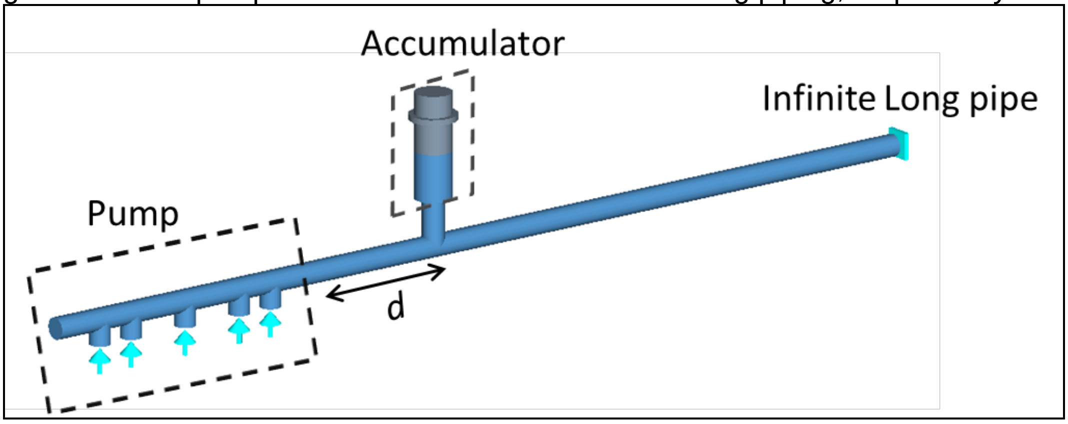

Figure 1 | Overview of initial Quintuplex model used for the computational design method using BOSpulse.

For the design study and comparison, all parameters regarding the pumps are fixed for either the triplex or quintuplex pump as described before. For the analytical design method main focus will be on the effects of changing the line pressure as well as the maximum required peak-to-peak pulsation level downstream of accumulator. For the computational design method more parameters are studies including accumulator gas volume, distance between pump and accumulator (*d*) and connecting branch diameter.
For the computational design method, some of the results are presented in Transmission Loss (TL) which defines a ratio between the final pulsations compared to the initial excitation in decibel for a

given frequency. Transmission loss can be a very useful output parameter when studying the dampening performance of an accumulator with different configurations.

$$TL = 20log_{10}\left(\frac{P_i}{P_j}\right)$$

where P_i is the initial pressure pulsation level generated by the pump, and P_j is the pressure pulsation level at point j of interest. For the current study, point i is located at the infinite long pipe boundary condition, as shown in *Figure 1*, unless stated otherwise.

The analytical design method does not describe the magnitude of the initial pump pulsations, therefore, the pipe diameter is used together with the frequency of the pump in order calculate change in velocity. The change of velocity is then related to the pressure change using Joukowsky's equation in order to calculate the initial pressure pulsation without accumulator.

Finally, the predicted pulsation levels using the two design methods are also compared to the pulsation allowable as defined through the API674.

Meeting the API 674 pulsation limit at an initial design stage taking only the pump and accumulator into account does not imply the API 674 limit will be met when the connecting piping is added. The level of resonance in the complete system determines the level of pulsation. Therefore, a safety with regards to the maximum of amplification due to resonance allowed can be defined as the ratio between the initial predicted pulsations and the API 674 limit in order to measure the effectiveness of the initial design. A larger safety implies a better initial design as the pulsations will remain within the API 674 at higher levels of resonance.

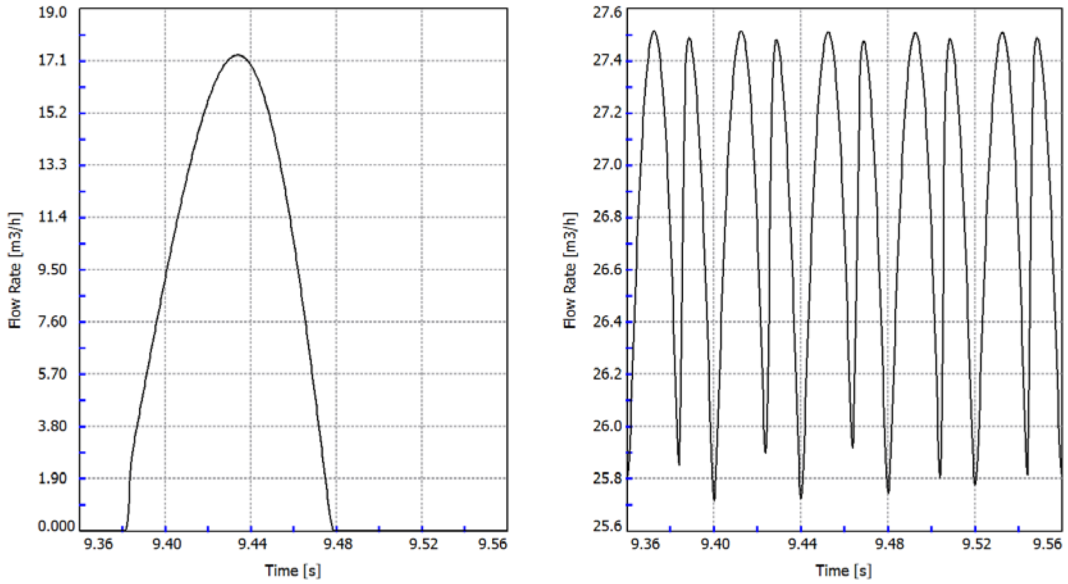

Figure 2 | Flow rate profile for quintuplex pump, single cylinder (left), combined profile five cylinders (right)

Initial frequency spectrum for pumps studied

Both a triplex and a quintuplex pump are studied in this paper. Each of these pump generate pressure pulsations with a distinct initial frequency profile. The profiles are generated using the BOSpulse reciprocating pump module. The flow profile for the pump is simplified ignoring any clearance volume and valve characteristics. The flow of both a single piston as well as the combined flow profile generated by the quintuplex pump is shown in *Figure 2*. A similar flow profile is generated for the triplex pump. The fluctuating volume calculated using the analytical method are 0.039 and 0.015 L for the triplex and quintuplex respectively. For the computational design method these values are around the 0.037 and 0.019 L. Each pump generates pulsations at fundamental frequencies. These frequencies can be computed using the following equation:

$$f_{fun} = n * N * f_{speed}$$

where f_{fun} is the fundamental frequency [Hz], N is the number of cylinders of the pump, f_{speed} is the operating speed of the pump [Hz], and n is an integer from 1 to (theoretically) infinite. The amplitude of a pump is typically the largest at the first two fundamental frequencies.

The frequency spectrum of pressure pulsations generated for the triplex and quintuplex pumps are shown in *Figure 3*. Pulsations at higher fundamental frequencies are also included but have decreasingly smaller amplitude.

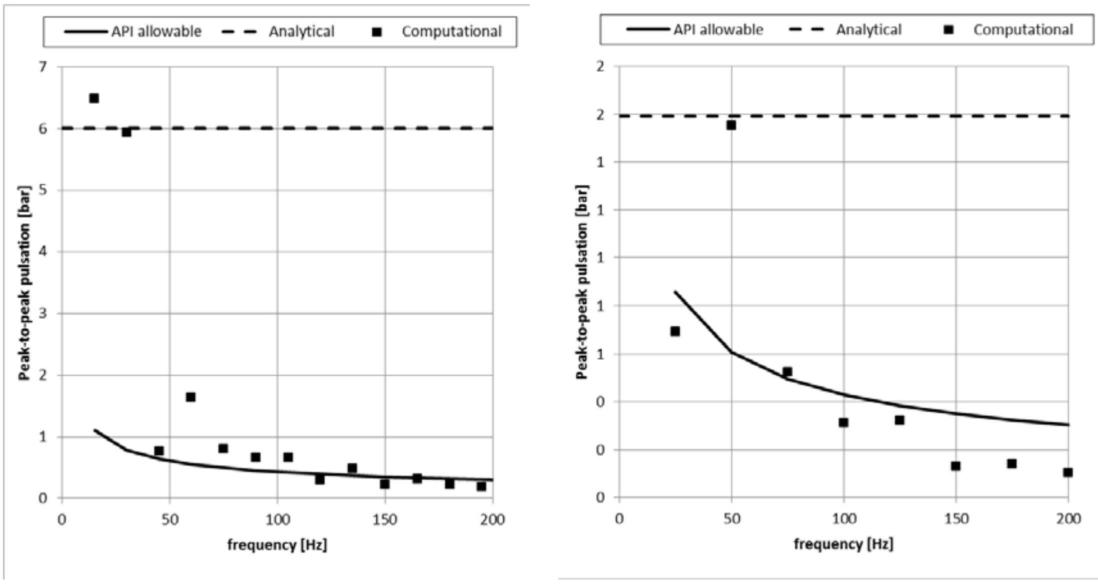

Figure 3 | Initial peak-to-peak pressure pulsation frequency spectrum. Triplex (left), Quintuplex (right).

Optimal initial accumulator design

For each design change a single parameter is changed while other design parameters remain constant. An accumulator volume of 7L at charging pressure is used for the base test case.

Volume and line pressure

For the analytical sizing method pulsation level is often reported as relative to the line pressure. However, experience has shown that the final pulsation level does not show significant dependence on the overall line pressure. Using the analytical method, the predicted pulsation level is small for a given accumulator volume at a low line pressure relative to that of a similar system at high line pressure. This is confirmed in the API 674 as the pulsation limits are also independent of line pressure. EPC's and OEM's should therefore be cautious when designing a system based on the predicted pulsation level using the analytical method.

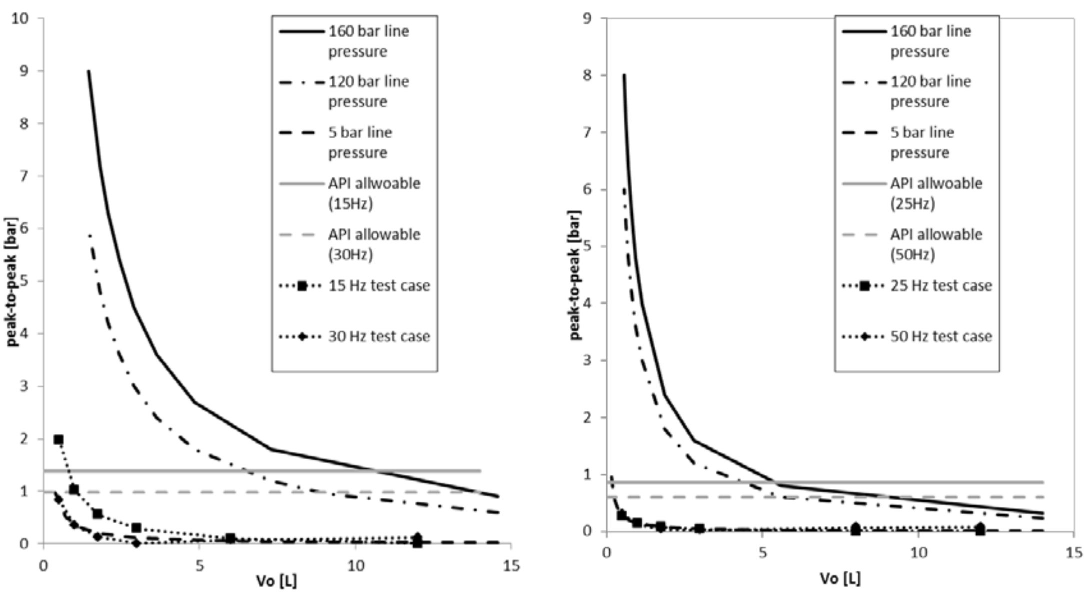

Figure 4 | Comparison predicted initial peak-to-peak pulsations analytical method and computational method with API limits, Triplex pump (left), quintuplex pump (right).

Figure 4 shows the peak-to-peak pressure pulsation level predicted using the analytical as well as the computational method for the triplex and quintuplex pump system for several variations of accumulator volume and line pressure. This figure shows the dependence of the analytical method on line pressure. If the accumulator is sized based on the API limits using the analytical method, the accumulator volumes would be in a reasonable range of 4 to 12L for the higher line pressures. However, when the line pressure is low, for example at a suction side or low pressure discharge side, very low accumulator volumes can be predicted by the analytical sizing method. The computational method also predicts relatively low accumulator volumes required. However, the design of an accumulator should not be based on this figure only as the goal is to obtain the largest safety with respect to the API 674 limits in the initial design.

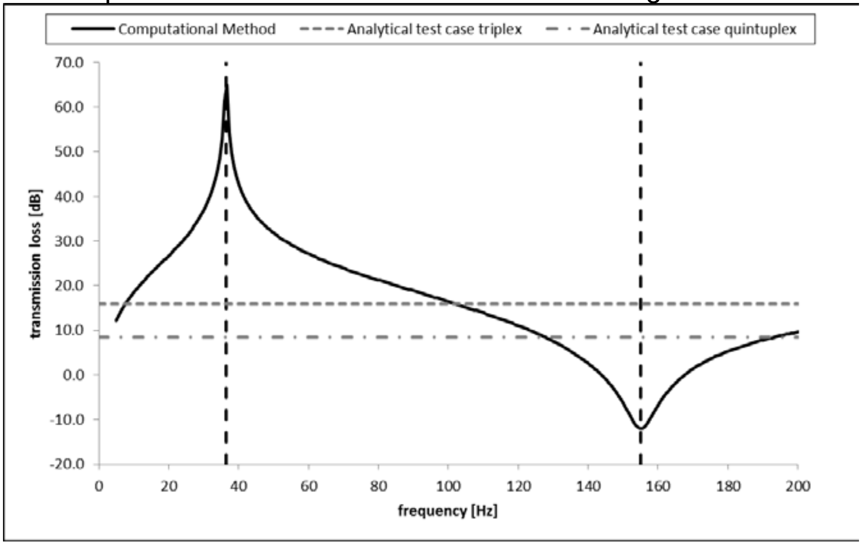

Figure 5 | Typical transmission loss profile branch connected accumulator.

Typical transmission loss profile branched type accumulator

For a better design of the accumulator the safety at each fundament frequency should be as large as possible. For this purpose a transmission loss profile is useful. A typical transmission loss profile for a branched type accumulator of the type studied in this paper is shown in *Figure 5*. The profile has two characteristic points which represent the natural frequencies of the pump / accumulator system. The first point represents the point of maximum dampening f_{opt} (~37 hz in the figure), and the second point is that of maximum amplification f_{res} (~155 Hz in the figure).

The goal of the initial accumulator design is to create a transmission loss diagram for which f_{opt} is at the frequency at which the pump produces the largest pulsations as well as to ensure that f_{res} is high enough in order to sufficiently dampen higher frequency pulsation components produce by the pump. This results in a design for which the largest possible safety is obtained at all frequencies of interest. Note how the analytical method predicts a constant transmission loss. The predicted transmission loss for the quintuplex pump is negative which is highly unrealistic.

Design study; gas volume

Figure 6 shows the result of changing gas volume at operating conditions. The results show that changing the gas volume mainly affects f_{opt} and not f_{res}. Increasing the gas volume reduces the location of f_{opt}. Changing the gas volume is therefore a very good way of setting the location of f_{opt} to ensure that the lowest fundamental frequencies are dampened. However, larger gas volumes could result in f_{opt} to become too low and the accumulator will not sufficiently dampen the frequencies produced at 50 Hz.

Design study; distance between pump and accumulator

It is normal operating practice for many OEM‘s and EPC’s to place the accumulator as close as possible to the flange outlet as possible. One might think that this good practice as an accumulator primarily reduces the pulsations downstream, not upstream.

Figure 7 shows the results in transmission loss for the change in distance between the accumulator and pump edge. Transmission loss is shown for both upstream and downstream of the accumulator are shown *Figure 7*. The upstream transmission loss is calculated using the pressure fluctuations at the pump flange.

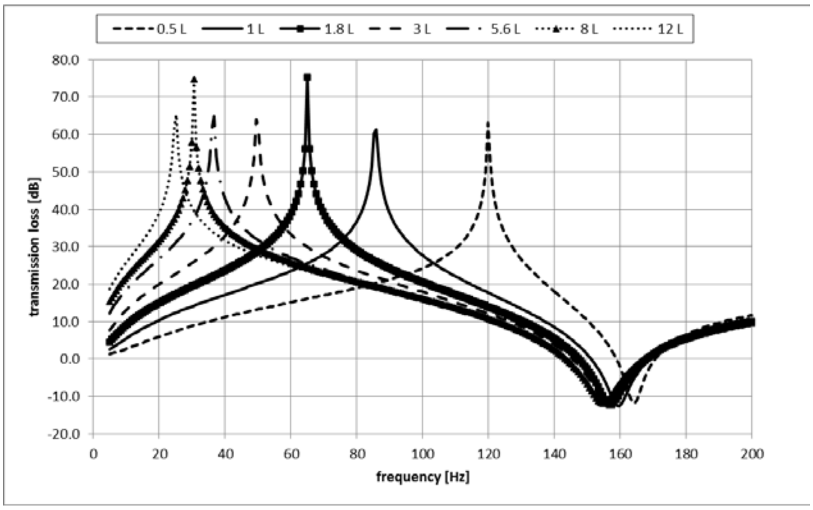

Figure 6 | Transmission loss for branch type accumulator with different gas volumes.

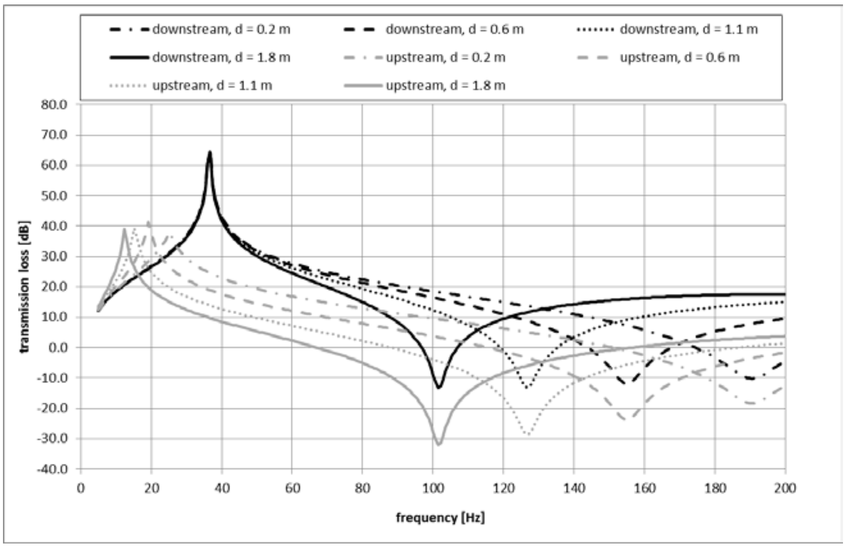

Figure 7 | Transmission loss for branch type accumulator both downstream and upstream of the accumulator for difference distances between the accumulator and pump flange.

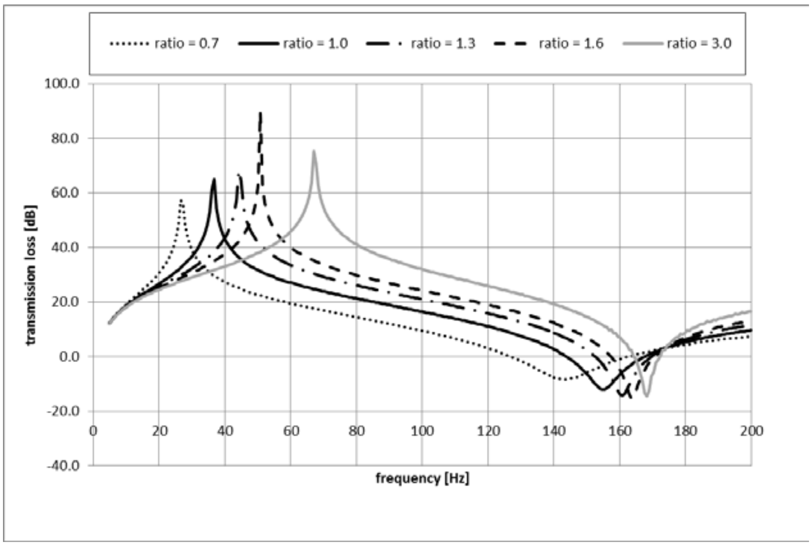

Figure 8 | Transmission loss for branch type accumulator using different branch diameters.

Regarding the downstream pressure pulsations, changing the distance only affects f_{res}, and an increase in distance decreases f_{res}. This can lead to a significant increase in pulsations at higher frequencies or even at the lower fundamental frequency of the pump if increased even further.

Figure 7 also shows that the accumulator reduces the pulsations between the pump and accumulator. This is of interest when low pressure at the suction side of the pump might cause problems in the form of cavitation. If the distance *d* is decreased the accumulator will more effectively dampen the pulsation upstream reducing the risk of cavitation when facing low NPSH. Placement of the accumulator further away can cause significant amplifications of the initial pulsations generated by the pump between the pump and accumulator as the transmission loss becomes negative at around the 60 Hz and remains negative for higher frequencies. The location of f_{opt} for the downstream transmission loss is independent of the distance *d*, and only depends on other characteristics such as volume and branch diameter.

Design study; connecting branch diameter

Another interesting design variable can be the branch diameter connecting the accumulator to the main header. When pressure pulsations reach a tee connection, part of the pulsation will reflect, the remaining part is transmitted to the downstream pipes. The amount of reflection and distribution across the downstream connecting piping is dependent on frequency as well as the diameter ratios between the different pipes. *Figure 8* shows the transmission loss for different branch diameters. From this figure it can be concluded that increasing the branch diameter results in (1) increased value for f_{opt} and (2) small reduction in f_{res} and (3) an increase of the overall effectiveness of the accumulator by increasing the maximum amount of dampening as well as increasing the maximum amount of amplification. The branch diameter should therefore be sufficiently large in order to guarantee a sufficient effectiveness of the accumulator.

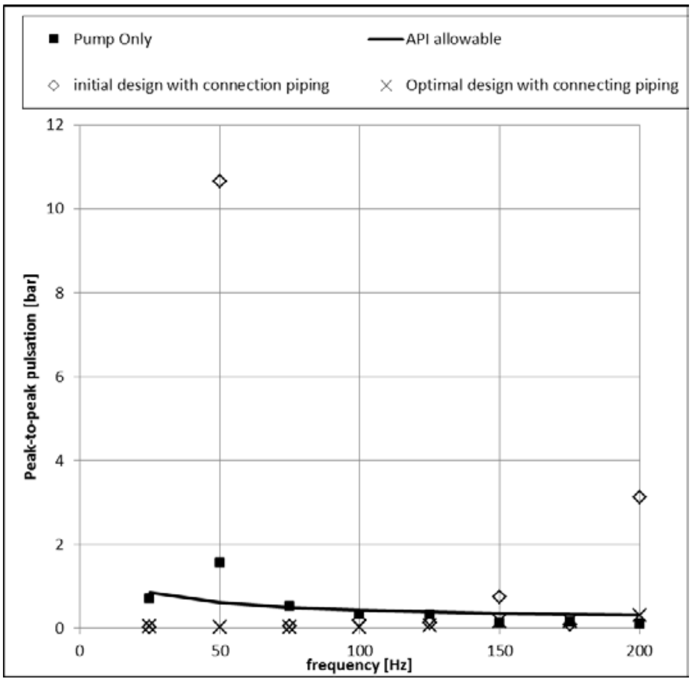

Figure 9 | Pulsation level resonance example for initial design and optimized design.

Example resonance and optimized design

The accumulator used in the test case for the quintuplex pump can be optimized in order to create a larger safety at 50 Hz as well as increase the frequency of f_{res}. This is done by selecting an accumulator volume of 3L instead of 7L and place the accumulator closer to the pump flange. The calculated safety at 50 Hz is increased from 11 to over 800. The optimized design has significant improvement of safety across the full range of frequencies.

In order to illustrate possible effects of resonance in the downstream piping a test model is created by adding connecting piping to the initial pump/accumulator system for the quintuplex pump shown in *Figure 1*. The total connecting piping has a length of ~13m and a fixed pressure, representing a vessel or injection into a gas line, is placed at the end. Resonance occurs between the pump and the pressure boundary condition at 50 Hz. *Figure 9* shows the final pulsation levels for the system with connecting piping. From this figure it can be noted that even though the initial design did reduce the pulsations at 50 Hz, the resonance in the system caused the pulsations to severely exceed the API 674 allowable at 50 Hz. The optimized design ensured additional safety and even though resonance occurs in the system, the pulsations remain within API 674 allowables.

Conclusion

There is a lot of variability in accumulator performance depending on factors other than volume as is used in the analytical design method. Moreover, the analytical design method can be misleading as an increase in volume does not always result into lower pulsations and the predicted pressure pulsations can significantly deviate from the actual pulsation levels when different line pressures are used in the calculations. The computational method shows that the accumulator should always be placed as close to the pump as possible and the branch connection should have a sufficiently large diameter compared to the header diameter.

Often computational studies are only used for the whole system. Here it is shown that a lot of benefit can be achieved by considering only the pump skid early in the design phase. The computational design method proposed in this paper offers more insight into the initial design of an accumulator compared to the analytical method and can create a more robust initial accumulator design in terms of safety with regards to the API limit. This safety represents the allowable amplification caused by resonance in the connecting piping. The example shown in this paper illustrates the effects of resonance through the downstream piping and how an optimally designed accumulator can prevent the high pulsations at an initial design stage.

Using this initial design method an OEM or EPC can calculate the safety margin with respect to the API limits at an early design stage, reducing the risk of requiring design changes once the complete system design including piping is finalized.