Practical design processes

Dr. Klaus Brun, Brian Pettinato and Marybeth McBain, Elliott Group; Dr. Rainer Kurz, Solar Turbines; and Eugene L. Broerman, Southwest Research Institute, discuss eliminating the risk of acoustically induced pipe vibrations in centrifugal compressors.

Periodic blade-pass pressure pulsation excitations from the suction and discharge of centrifugal compressors can cause acoustic resonance conditions and associated pipe vibrations upstream and downstream of the compressor. These high frequency pressure excitations are usually created by the translation of non-uniform jet-wake meridional flow of the first or last stage compressor impeller blade passages from the rotating impeller to the stationary suction/discharge piping frame. The excitation frequency of these blade-pass pressure pulses, relative to the stationary frame, is determined by the speed of the compressor multiplied by the number of impeller blades. The potential of these types of vibrations to cause structural damage to the pipe and pipe small bore connections has been well documented.

Although both Helmholtz resonators and quarter wave absorbers are effective in reducing first order singular frequency pressure pulsations, they cannot remove or attenuate higher orders of these periodic excitations. They also effectively shift first order excitations to the second order, and if not carefully designed, can actually create damaging higher frequency acoustic resonances in the upstream/downstream piping. However, a series of two or more progressively placed quarter wave resonators, called a quarter wave comb filter, can be designed to shift excitation frequencies multiple orders higher, such that their pulses superimpose to form a continuous steady waveform.

Case study and parametric optimisation

This case study discusses the practical design of such a comb filter, its installation in the downstream piping near the discharge of the compressor, basic comb filter design guidelines, a step-by-step design process for comb filters, and quantification of its attenuation effectiveness. Although the case study is based on a multi-stage compressor, only pulsations from the last stage in the compressor were analysed and attenuated. Also, the compressor used a vaneless diffuser such that only blade-pass frequency pulsations at the running speed were of relevance.

Operating conditions:

- Speed: 7000 rpm (116 Hz).
- Impeller tip diameter/no. of blades: 10 in. (25.4 cm) 16 blades (no splitters).
- Process gas: natural gas (SG=0.62).
- Discharge pressure/temperature: 80 bara/40°C.
- Discharge pipe diameter: 9 in. (20.3 cm).

Based on these operating conditions, the primary fixed speed blade-pass excitation frequency is 1867 Hz, and the predicted periodic excitations at the compressor discharge are 0.2 bar. This excitation frequency coincides closely to an acoustic two-pipe diameter radial mode in the discharge pipe at 1875 Hz, and a radial pipe resonance would be expected. The excitation pressure trace was conservatively assumed to be a square wave to make sure the comb filter design properly attenuates higher order frequencies.

A quarter comb filter was designed based on the speed of sound of the process fluid at the discharge pressure and temperature (445 m/sec.) and the given blade-pass excitation frequency. The resulting comb filter for this case study was for the first-stage quarter wave filter. Seven circumferential, evenly spaced stubs were placed 10 cm downstream from the compressor discharge flange. The second and third stage filters were offset, placed 5 cm and 10 cm downstream from the first stage. Each row has seven quarter wave resonator stubs, resulting in a total of 21 stubs (Figure 1).

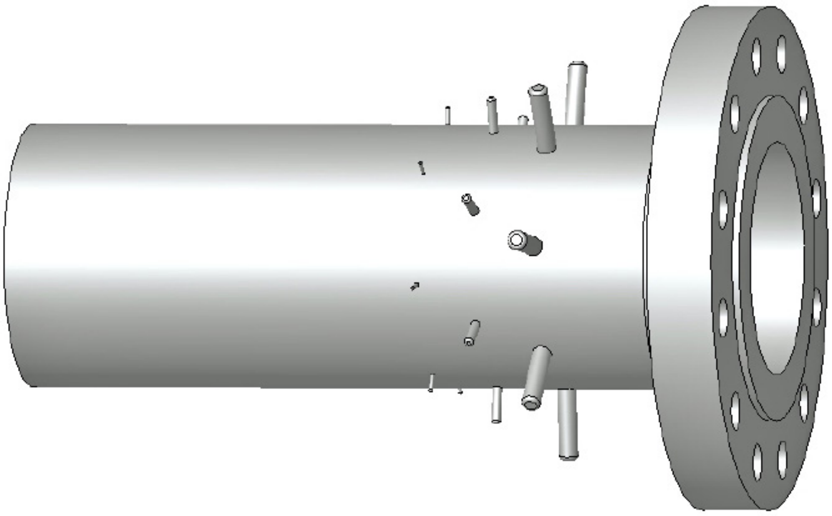

Figure 1. **Comb filter design.**

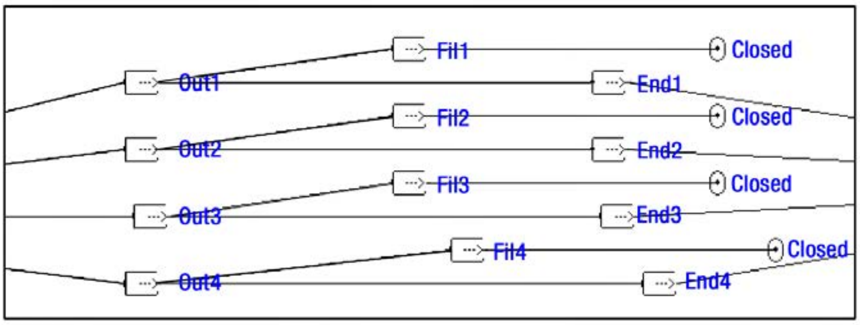

Figure 2. **Transient model for Case B.**

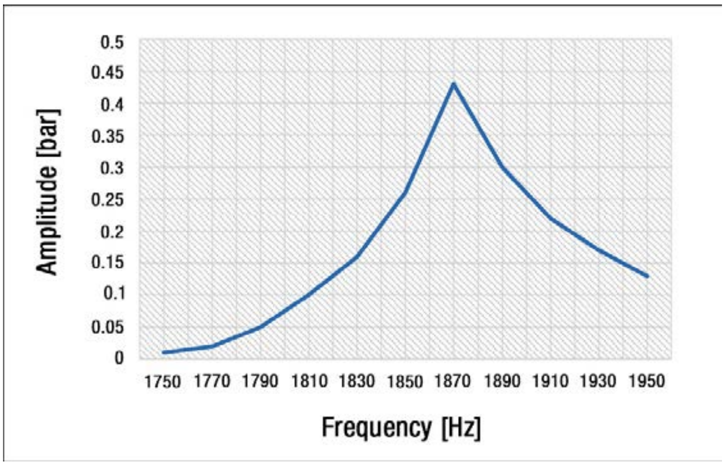

Figure 3. **1x frequency response plot sweep with no comb filter.**

Case study analysis

A new 1D Lax-Wendroff method time-domain flow solver was developed to determine the highly transient fluid pulsations in centrifugal compressors and their associated piping systems. This flow solver is governed by a system of three equations addressing continuity, x-momentum, and energy. The solver includes all terms of the governing equations, including fluid inertia, diffusion, viscosity, and energy dissipation. The solver moves forward in time, and at each time step, boundary conditions at the segment end nodes were recalculated and enforced. A Peng-Robinson equation of state was used to determine gas physical properties at each node and time step.

For this specific excitation and comb filter design, the following four cases were numerically analysed:

- A. No comb filter.
- B. First stage quarter wave filter only.
- C. First and second stage comb filter.
- D. First, second, and third stage comb filter.

For each of these cases, 1D transient analysis models were built in the aforementioned solver. Figure 2 shows a typical analysis model for Case B. The frequency range was swept from 1750 Hz to 1950 Hz to capture the filter's effective band range for each model.

Results from the case study are shown in Figures 3 and 4. Figure 3 shows only the first order 1X frequency sweep results for Case A. Figure 3 also shows that although the excitation amplitude at 1867 Hz was only 0.2 bara, the response in the pipe is significantly higher, reaching almost 0.44 bara due to the two-diameter pipe resonance at 1875 Hz.

Figure 4 shows the 1X pipe system response for all cases. The attenuation effectiveness of the comb filter case design can easily be compared here.

As expected, Case A, with no filter, shows a typical frequency distribution of a mildly smoothed square wave. Case B shows that a single row of quarter wave resonators effectively halves the amplitude of the pulsations but also shifts some of the energy of these pulses to the second order. When a second row of quarter wave resonators is used, as shown for Case C, the second order pulsations are significantly reduced, although in this case, some of the second order energy should have been shifted to the fourth order. These high frequency pulsations are naturally damped by the fluid's viscosity such that they are not seen to be significant. Similarly, Case D, with three rows of filters installed, effectively eliminates the pulsations. However, the pulsation attenuation improvement between the two-stage and three-stage comb filter is seen to be minimal. In all studied cases, pulsations at the third and fourth order (i.e. above 5000 Hz) were not found to be relevant.

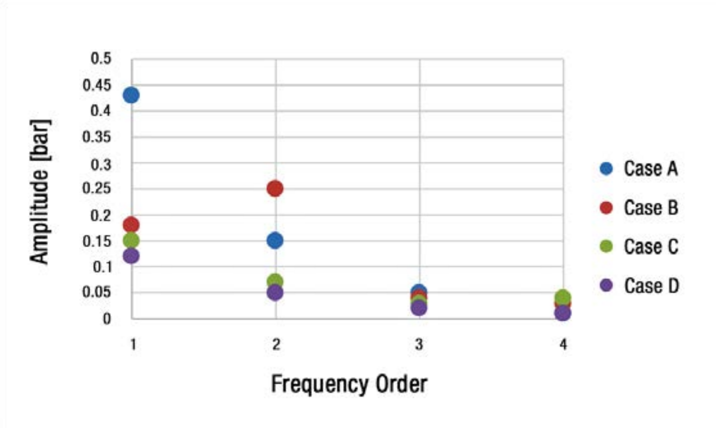

Figure 4. Pipe system response for Cases A, B, C, and D.

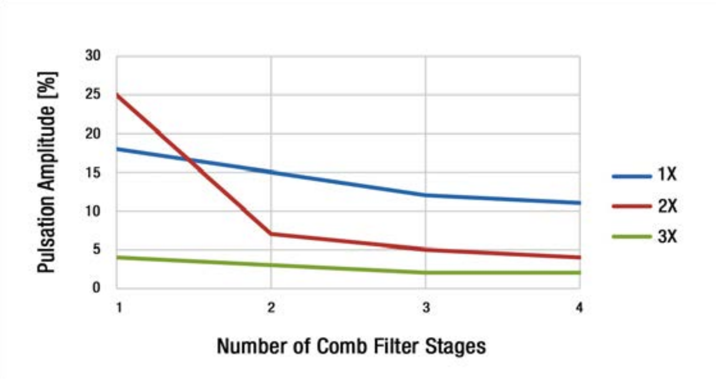

Figure 5. Pulsation amplitude vs number of comb filter stages.

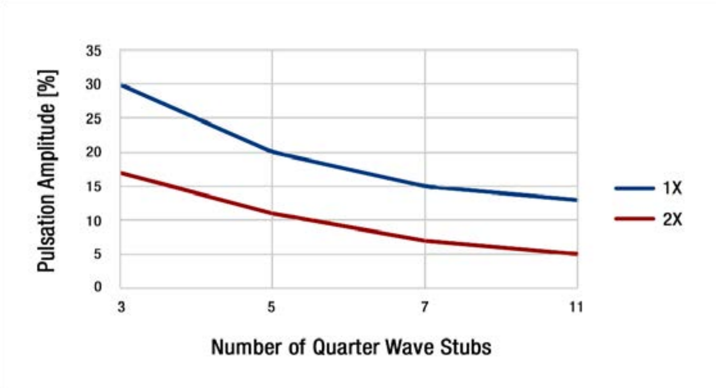

Figure 6. Pulsation amplitude vs number of quarter wave stubs per stage.

Parametric studies

Several parametric studies were conducted to evaluate the effect of various comb filter design options, including number of stages, number of circumferentially placed resonators, and total resonator cross-sectional area. The comb filter design discussed previously was used as the baseline design, and design parameters were varied to determine their impact on the lower order pulsations, although some of the results can be generalised to develop basic comb filter design guidelines.

Figures 5, 6 and 7 show results from some of the parametric studies. The amplitude results are normalised by the Case A baseline results such that the resulting numbers effectively represent a percent of filter effectiveness. For example, Figure 5 shows the percent pulsation amplitude for the first, second, and third order pulsations as a function of the number of comb filter stages. As anticipated, a single quarter wave filter stage effectively attenuates 1X pulsations, but amplifies 2X pulsations. A comb filter with two stages addresses this issue by removing most 2X pulsations. Little difference is seen between a two, three, or four-stage comb filter design. Similar results from other studies indicate that in most cases, a two-stage comb filter design adequately addresses pulsation resonance problems and further comb stages are unnecessary.

It is important to determine the appropriate number of quarter wave stubs and their diameter. Figures 6 and 7 provide case studies for these design variables with Case C as the baseline. Specifically, Figure 6 shows the impact of a number of stubs (keeping their diameter constant) on pulsation amplitude, and Figure 7 shows the impact of stub diameter (keeping their number constant at 7) on pulsation amplitudes. It should be noted that in Figure 6, the x-axis is total quarter wave stub cross-sectional area as a percent of total pipe cross-sectional area. As anticipated, both charts show similar results. The pulsation amplitudes decrease non-linearly with the number of stubs and the stub diameter. Figure 6 shows that beyond a 15% cross-sectional area, the improvement in pulsation attenuation is not significant.

Comb filter design

Based on the described parametric studies, past analysis cases, acoustic filter design literature, and experience with testing quarter wave resonators, a number of comb filter design guidelines and a step-by-step methodology can be developed for centrifugal compressor blade-pass pipe radial resonance attenuation.

Design guidelines

The following design guidelines were developed based on specific cases and may not always be applicable for all comb filter designs.

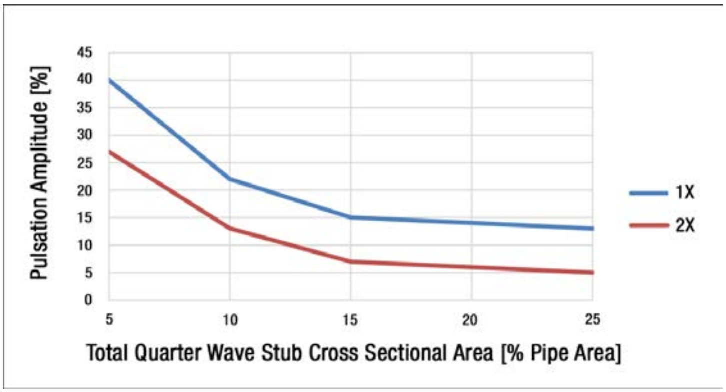

Figure 7. Pulsation amplitude vs total quarter wave stub cross-sectional area.

- A minimum of three evenly circumferentially spaced quarter wave stubs per stage should be used.
- The total cross-sectional area of first-stage quarter wave stubs should be at least 15% of the pipe cross-sectional area. For second-stage stubs, the cross-sectional area should be at least 7.5% of the pipe cross-sectional area.
- The number of stubs per stage should be prime numbers to avoid radially opposing close-end cross resonances.
- Downstream quarter wave stubs should be circumferentially offset from upstream absorbers to avoid inducing resonances from upstream vortex shedding.
- The first-stage comb filter should be as close to the compressor flange as possible from a design and maintenance perspective. Subsequent stages should not be more than 10 cm upstream/downstream from the previous stage.
- The diameter of each quarter wave stub should be approximately 5 - 15% of the pipe diameter.
- The quarter wave stub aspect ratio should not exceed 1:4 to avoid 3D effects.
- The quarter wave stub aspect ratio limits the total cross-sectional area of each stub, and the total number of stubs is driven by the need to absorb sufficient pulsation energy.
- Usually two rows of comb filter stages are sufficient, but analysis should be performed if there is a concern about very high frequency excitation.

Design process

Based on these design guidelines, the basic comb filter design process is reasonably straight forward and can be summarised as follows:

- Calculate the quarter wave stub length for the first, second, and third-stages based on the desired attenuation frequency and gas speed of sound. Specifically: length [m] = speed of sound [m/sec.] / 4 * frequency [Hz].
- Determine the stub diameter by not exceeding a diameter-length aspect ratio of 1:4 and considering commercially available pipe sizes.
- Calculate the number of stubs required to have the total cross-sectional area of all stubs be no less than 15% of the pipe's cross-sectional area. The number of stubs should be based on a prime number, with a minimum of three.
- A minimum of two comb stages should be used to avoid second order pulsations.
- The second-stage stubs should be half the length and half the diameter of the first-stage stubs.
- For the second stage, the total cross-sectional stub area should be at least 7.5% of the total pipe cross-sectional area.
- The second row does not have to have the same number of stages as the first row, but stubs should be radially offset between stages.
- A third row of comb-filter stages is usually not necessary unless there is a concern about very high frequency pulsations. In this case, the design guidelines of the second stage can be followed.

Summary

The excitation frequency of these blade-pass pressure pulses relative to the stationary frame is calculated from the speed of the compressor multiplied by the number of impeller blades, and if this excitation frequency coincides with a flange radial acoustic piping mode or a short segment pipe axial mode, resonance and significant associated pressure force induced piping vibrations can result.

A series of two or more progressively 50% length-decreasing quarter wave resonators, also called a quarter wave comb filter, can be designed to shift excitation frequencies multiple orders higher, such that their pulses superimpose to form a continuous steady waveform. This can almost completely filter out all excitations. The advantage of a comb filter over Helmholtz arrays is that they can handle the multiple frequencies and higher orders of complex wave forms that are typically seen from centrifugal compressor blade passing pulsation excitation and from a mechanical perspective, they are significantly easier to install in compressor connected piping.

This study addressed the practical design process of such a comb filter, its installation in the downstream piping near the discharge of the compressor, simple design guidelines, and provides a basic case study modelling results and predictions of its effectiveness. Related parametric studies showed that two to three-stage comb filters can be effectively used to eliminate centrifugal compressor blade-pass excitation induced pipe radial resonances and associated vibrations. The design and installation of comb filters on new or existing compressor installations is relatively straight forward since standard pipe components can be used. The results of this study provide clear, concise, and detailed instructions on how to design an effective comb filter for a centrifugal compressor application.