Preliminary piping sizing and pressure pulsation evaluation
Abstract:

Low-Density Polyethylene (LDPE) production requires processing equipment with increased capacities and existing applications uprating. This includes large reciprocating compressors with several cylinders operating at very high pressures. Since these special components, including reactors and intercoolers, have very long delivery times, selection of piping size requires a careful analysis to be performed at an early stage of a project so that the costs can be estimated properly. A preliminary evaluation that uses the compressor data sheet and piping and instrumentation (P&I) diagram should be made during the bid stage. A specific pre-study linked to the compressor sizing program can be used for preliminary cost estimation.

Before issuing a piping purchase order, based on the first issue of real layout around the compressor, the preliminary evaluation must be confirmed by a preliminary pulsation study.

Once the plant arrangement is complete, a final acoustic study must be performed. Usually, such a study only results in minor adjustments to the design and doesn’t involve the piping size.

Nomenclature

- \( a \): Sound velocity (m/sec)
- \( A \): Cylinder bore (m)
- \( API \): American Petroleum Institute
- \( ASME \): American Standard Mechanical Engineers
- \( Coef \): Coefficient for harmonic sum & resonance amplification
- \( D_{kn} \): Oscillation amplitude of the \( k \)th degree of freedom in the natural mode
- \( EPC \): Engineering, procurement and construction
- \( F_n \): Generalized force of \( n \)th mode \( \sum j m_j D_{jn} \)
- \( FE \): Finite Elements
- \( HE \): Head End
- \( K \): \( C_p/C_v \) ratio
- \( LDPE \): Low-Density Polyethylene
- \( m_n \): Generalized mass of the \( n \)th mode \( \sum j m_j D_{jn} \)
- \( MW \): Molecular Weight
- \( N \): \( N \)° of degrees of freedom, equal to the \( n \)° of the natural frequencies that can be calculated
- \( P&ID \): Piping & Instrumentation Diagram
- \( p.to.p. \): Peak to Peak
- \( r \): Stroke/2 (m)
- \( RPM \): Revolutions per Minute
- \( S \): Pipe cross section area (m2)
- \( t \): Time
- \( X \): Coordinate distance along the axis of the tube from an arbitrary origin
- \( x_k \): Displacement of the \( k \)th degree of freedom
- \( \Delta p/pm \): Pressure pulsation % peak to peak
- \( \div \): \( 2 \times \text{RPM} / 60 \)
- \( \theta_n \): Angle of phase
- \( \omega \): Exciting frequency
- \( \omega_n \): Frequency of the \( n \)th mode shape
- \( \zeta \): Fraction of critical damping
Introduction

New LDPE projects or existing application up-ratings with increased equipment capacities always involve constraints on deliveries of piping and equipment. Therefore, an early design becomes increasingly important for the successful development of the project for both the end user and the supplier.

The bid stage usually is based on machinery sizing while the plant layout, apart from standard applications, is defined in a later stage.

LDPE plants have critical equipment like booster-primary and hyper compressors that must reach very high pressure for the proper reaction. Because these machines generate pressure pulsations inside piping and their operation can be subject to severe vibrations, these effects must be properly evaluated.

While attention must be paid to the design of pulsation suppression devices and standard piping on booster-primary compressors, this is not as critical as the design for the tubular reactor plant where the sizing is fundamental for several aspects of the project:

- **Pressure pulsation induced forces.** Hyper applications do not include dampeners (due to the extreme pressures), so the pressure pulsations that occur during operation could be very high. This leads to severe vibration problems during plant startup and accompanying production losses.
- **Delivery time for piping and equipment.** High operating pressure requires very special piping, reactors and intercoolers with a long delivery time, so decisions must be made at a very early stage to keep the project on schedule.
- **Piping and equipment cost impact.** Since the piping and equipment are specifically manufactured for the LDPE application, their sizing strongly influences the cost. Hence, it’s extremely important to make a careful analysis during the bid stage to properly estimate the costs.

The situation could be improved by performing a preliminary pulsation evaluation during the bid stage. This would account for the cylinders and common piping sizes, while the rest is approximated as a non-reflective line by using a method similar to API 618 Approach 3 Pre-study Para 7.9.2.3.4 [1]. Based on the evaluation results, a proper cylinder connection arrangement and a suitable piping size can be selected and used to estimate piping costs.

### Hyper Compressor Operation

#### Necessary studies

Depending on process and reactor type [4, 5, 11], secondary compressors reach reactor pressures ranging from around 100 MPa (15,000 psi) up to 350 MPa (50,000 psi). Hyper compressors (Figure 1) are the heart of these plants and, together with the high pressure piping systems, are fundamental to reliability and availability [4, 5].

The unsteady gas flow of reciprocating compressors generates pressure pulsations that might be increased by acoustical resonance. Depending on plant configuration and fluid characteristics, this can cause high vibrations, high noise levels and reduced performance [6, 7, 8]. Therefore, it is necessary to make very detailed analyses – particularly for high-pressure piping – to prevent failures from cyclic stresses that result from:

- Piping vibrations induced by the pulsations
- Vibrations transmitted by the machine
- Thermal expansions of the piping

The extent of the vibrations depends on the:

- Amplitude and frequency of the pulsations
- Amplitude and frequency of the compressor loads
- Elasticity, mass and damping of the mechanical system

The studies to be performed are:

- An acoustical analysis, to avoid acoustical resonance and control the pressure pulsation level. This usually is divided into three steps:
  - A bid-stage evaluation of residual pressure pulsation
  - A preliminary-acoustical analysis at the beginning of the project
  - A final acoustical study based on final piping data
- A mechanical analysis of the complete system, to avoid mechanical resonance and prevent dangerous vibrations and stresses [3, 4]

In hyper applications (Figure 1) acoustic filters (volume bottles or dampeners) are generally too expensive to be used because of the high walls thickness and auto-frettage treatment that would be needed to manufacture them [6].

The acoustic damping effect of piping is low, so the most effective way to limit vibration is to limit, as much as possible, the residual pressure pulsation and the relevant induced forces.

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Figure 1

Hyper compressor arrangement
Pulsation control

In all complex and critical plants, the entire system subjected to pressure pulsation (i.e., to the proper boundary point) must be analyzed in all operating conditions [6]. This includes the piping, cylinders, valves, orifices, intercooler, pre-heater and tubular reactor.

At all significant pressure pulsation levels, the shaking forces acting on the equipment and piping must be calculated and compared with the limits suggested by the experience or, specifically, by the customers.

The bid stage evaluation usually is based on the machinery sizing, while the plant layout, apart from standard applications, is defined in a late stage.

It takes a very long time to deliver piping, valves and fittings to LDPE plants because of the very high pressures involved [5]. To shorten that delivery time, the orders must be issued early in the design stage and before carrying out an accurate acoustic study, since the final layout is not available.

There are additional considerations to be made [5,6,8,9]:

- At very high pressures, the speed of sound in ethylene varies considerably with the pressure and temperature.
- Since the compressors operate in a wide range of pressures and temperatures, several conditions must be studied to fully cover the operating range.
- Since these pressures yield a very high speed of sound (ranging from 1,000 to 2,000 m/sec.) and very long wavelengths (300 to 600 m), ensuring a reasonable separation from resonance requires that piping length changes (and changes in the position of branch piping connecting points) must be on the order of dozens of meters. Apart from being difficult and costly to implement, such a length can only be determined after studying the final layout – at which point this kind of modification might no longer be feasible.

Given these application constraints, the most frequent remedy, when the plant layout is fully defined, is the use of orifices to reduce the acoustic resonance amplitude.

While orifice pressure drops can significantly reduce the resonance amplification effect, they can't reduce the pulsation level below the combined pressure pulsation generated in the common endless line (i.e., without acoustic reflective effect). It is only possible to comply with the desired pulsation levels by limiting the combined pressure pulsation on the common line. The combined pressure pulsation generated in the common endless line can be calculated by a dedicated bid-stage pre-study evaluation that just uses the compressor data sheet (i.e., thermo-dynamical data) and P&I diagram (i.e., to consider pipe size and cylinder stream connections required by the EPC process). To be cost-effective and comply with bid timing, this first pressure pulsation sizing evaluation should be linked directly to the compressor sizing program so that all operating cases and possible subsequent adjustments can be directly considered. When the evaluation is based on endless line calculation, a certain amplification of the value must be considered to obtain the desired pressure pulsation level. Therefore, the calculated combined pressure pulsation generated in the common endless line must be compared with the required allowable value by using a safety margin similar to the one used by API 618 Approach 3, Pre-study Para 7.9.2.3.4 [1, 8].

Experience shows that a 30 percent margin usually is sufficient to obtain the required pulsation value. These results show that a suitable piping size and arrangement can be identified and therefore used to estimate piping costs.

Best Practices (for the First Design)

Some rules applied in the first design of the piping layout can reduce modifications arising from the acoustic study and limit the number of orifices required to manage pressure drops, leading to a smaller piping diameter or, for the same diameter, to lower pulsations [5].

From the first design, the process and plant layout designers must consider some fundamental drivers of pressure pulsation limitation that allow the correct pipe size to be selected.

Piping Design

Static and dynamic cyclic stresses

First, the selected piping sizes and thicknesses must withstand the static (operating-design pressure) and dynamic (pressure pulsations) loads. Hoop stress is the main contributor, compared to the axial [stretching] and the radial [the lowest] stresses. Based on extensive experience, the hoop stresses at the OD must be limited to 21 MPa (3,000 psi) [1, 2] to avoid piping failures underneath supports on unjacketed HP pipes.

A larger internal pipe size significantly increases the pipe thickness necessary to maintain the static stress within the limits, and consequently increases pipe weight and relevant cost. At the same time, a larger pipe size reduces pressure pulsation and, consequently, dynamic hoop stress.

Thermodynamic aspects

The selected piping size also must reduce piping and equipment pressure drop. Therefore, gas velocity must be adequate to maintain plant performance and avoid useless energy consumption. The allowable gas velocity is a function of several parameters such as operating pressure, plant lengths (higher lengths yield higher pressure drop that must be considered in the process), and gas MW. Each company has its own standards and, consequently, limits based on experience, but it’s a good practice to keep gas velocity as low as possible to have a margin for future uprating.

Influence on compressor valves performance

The pipe also must be sized to account for the pressure pulsations effects close to the cylinders (i.e., up to the common line) that strongly influence the cylinder PV cycle, the valve operating behavior and life cycle [10].

For all of the reasons mentioned above, the pressure pulsations must be maintained within reasonable levels to avoid hurting compressor performance. To achieve that goal, the piping must be sized properly.
Allowable pulsation levels

Due to the high operating pressures, the hyper compressor applications are beyond API 618 approach 3, 5th edition [1] purposes and so are limited to 35 MPa (e.g., the applications would require a pressure pulsation of 1 percent peak to peak or less).

As there is no dampener, it is almost impossible to reach such requirements, so the pulsation-induced forces are much higher than those obtained in API application. Hence, the piping and plant equipment must have adequate supports and structures – whose design is critical – to control the relevant pulsation-induced forces and consequent vibrations.

This is why a customer’s previous experience in similar applications is fundamental when selecting the required residual pulsation values. Usually the requirement is to limit the maximum pressure pulsation within 5 ÷ 10 percent peak-to-peaks of the average operating pressure. The highest values generally occur near the cylinder flanges, while lower values occur on the common piping (i.e., in the part where multiple cylinder lines are connected together in a stream as the intercooler, preheater or reactor). As the common parts represent the largest portion of the plant, a lower pulsation level (half of the value at the cylinders is desirable) is essential to facilitate the supports design [5,8].

The piping or equipment, with jacketed piping and/or located on elevated structures, should experience reduced forces relative to the piping section near to the ground, where it is much easier to be supported.

Accounting for these factors, the plant and process designer should enhance the layout, because the piping layout, size, cylinder connections and crank angles can reduce the total (unfiltered) pressure pulsation amplitude and, consequently, create significant cost and plant operation benefits.

Approximated cylinder pulsation for pipe size definition

To evaluate the pressure pulsation at the cylinder flange, it is necessary primarily to estimate, through formula (1), the main harmonic component (in case of one single cylinder acting, the 1st harmonic corresponds directly to RMP). To account for plant acoustic resonances amplification and other harmonic components, a safety margin (Coef=1.3) is added to the initial formula used for a piping connected to an endless pipeline.

$$\frac{\Delta p}{P_m} = \frac{KA\omega r}{aS} \text{Coeff}$$

(1)

EPCs should use the above formula to verify the expected pressure pulsation value on the selected pipe size using data available on the compressor data sheet. When the resulting value is bigger than desired, the calculation must be repeated for a larger pipe size until an acceptable value is obtained. All parameters depend on application requirements and, consequently, are fixed; only the pipe section can be modified.

Results from the formula (1) show that the larger the pipe size, the lower the residual pulsation. But note that the larger pipe sizes will increase piping costs.

The pipe size of the common line should be equal to or bigger than the one relevant to each cylinder single line. Thus, the values obtained in the common line strongly depend on the cylinder connection combination.

Reducing shaking forces

The vibration problems are caused by the pulsation-induced forces (Figure 2). The oscillating forces are generated by the pressure pulsations that correspond to all the pipe discontinuities such as curves, pipe reductions, tee blocks, etc. Their amplitude depends on the amplitudes and phases of the pressure pulsations between discontinuities and pipe size.

Theoretically, for the same pressure pulsation, a bigger pipe size will get a bigger resulting force. For a real application, considering that the bigger the pipe size the lower the residual pulsation, these two effects are balanced. However, it is easy to mechanically control the same pulsation-induced force with a bigger pipe since it is more rigid and consequently requires a reduced number of supports.

The pulsation-induced forces are obtained multiplying the differential pressure pulsation between discontinuities for the cross pipe section (Figure 2).

At the beginning, the pressure pulsation phase among discontinuities (i.e., locations where forces are applied) is unknown. The real resulting forces can vary from a minimum of zero (if fully in phase) to twice the pressure pulsation multiplied by the pipe cross section (fully out of phase). Such a possible range of forces must be considered for the support and structure design, since usually the longer the distance between discontinuities, the bigger should be the resulting forces.

The highest values generally occur near the cylinder. Since discontinuities are concentrated in a short section of pipe with several elbows, such forces must be restrained by a limited number of supports. High forces also could occur even in case of lower pressure pulsation amplitude, when the pulsation between the elbows is out of phase. On LDPE applications, this occurs in a long straight line where several supports are available, so these forces can be critical only when they occur on elevated and flexible structures.

Besides having the desired residual pulsation levels, the selected pipe size should produce pulsation-induced forces that are suitable for the piping supports and structures design of the specific project.

In general, up to a certain value a bigger pipe size yields several technical advantages, but all aspects, including cost, must be duly evaluated.
Pulsation and Cylinder Phasing

Residual pulsation on common pipe strongly depends on cylinder phase combinations. The following examples (Figure 3) clearly show that to have a good combination coefficient, at least three or more cylinders equally spaced on the 360° must be connected.

1 cylinder Sum ~ generated
2 cyls Sum > = generated
3 cyls 120° Sum < generated
4 cyls (90°) Sum < generated
5 cyls (72°) Sum < generated

Figure 3. Example of cylinder combination sum

The following aspects must be considered to lessen such a combination:

- Three (120° phased), four (90° phased), or five (72° phased) cylinders, connected in a common stream line, create the best residual pulsations combination for a given diameter size [9].
- A connection properly designed among the cylinders produces a combined pulsation level that is considerably lower than the one relevant to a single cylinder.
- The use of stream with one or two cylinders should be avoided as much as possible as it creates higher residual pulsation compared to multiple cylinder connections. Otherwise, the Coef of formula (1) must be increased to an average of 2 (in practice the Coef may vary from 1.5 to 2.5 but is not unknown by EPC at this stage). After that, the exercise for the minimum pipe size must be repeated with the new Coef.
- The connection among cylinders must be designed as close as possible to the compressor to reduce the section of piping subjected to the highest pulsations levels.

In an application with two or more cylinders in the same stream, the connection among the cylinders must be made among those that are equally phase spaced. (For instance, with six cylinders at 120° the three on the same side must be connected. A related example could be the application of a 10-cylinder compressor, with five cylinders on each side (Figure 4) to be connected to the suction lines in the proper way.)

Also, the valve opening timing impacts the pressure pulsation sum but, depending on project requirements, can rarely be adjusted.

The crankshaft could be enhanced, according to the various previously mentioned arrangement possibilities. In this case, the 72° angular positioning was selected (Figure 5).

The above discussion shows that a proper cylinder phase connection combination is the most powerful parameter available for the designer to limit plant pressure pulsations and relevant issues in order to create a minimum pipe size requirement. Therefore, it is fundamental, until the initial definition of the process, to use standardized best connection solutions.

EPCs should use all the above best practices and then select the proper pipe size.
Pulsation Evaluation at Bid Stage

Innovative method for reciprocating compressors

The first P&I diagram provided by an EPC only shows the initial selected pipe sizes and cylinder stream connections. A simplified pre-calculation linked to the compressor sizing program can correctly estimate the plant thermo-dynamical data. This makes it possible to evaluate the approximate combined pressure pulsation generated in the common endless line. The tool, developed to calculate the residual pressure pulsation in the piping system, starts reading the running condition data from the compressor project database.

The tool is the same one used to calculate the residual pressure pulsation with dampeners. In the presence of dampeners it is possible to acoustically design the compressors to achieve a specific residual pressure pulsation target. This is an important program (for an API 618 application like booster-primary services) as it yields an exact estimate of the volume necessary to achieve a specific target for residual pulsations (API618 or unfiltered p.to p. percentage). This also makes it possible to correctly estimate the cost of this equipment already at the bid stage, rather than using empirical formulas.

The API 618 approach 1 method (initial commercial sizing) doesn’t allow for an evaluation of the volume necessary to achieve approach 3 pressure pulsation requirements. These empirical methods delegating the definition of the necessary dampeners sizing to the real project create cost uncertainty for the customer and manufacturer until the final sizing is defined.

Hyper application case

For hyper compressor applications without dampeners (Figure 1), the first step of the process is the calculation of the flow as a function of the time for each suction and discharge compression stage and for each interested cylinder. As the flow is a periodic function, a Fourier analysis is performed to convert the time domain function into a set of harmonic components with amplitude and phase. Next, the harmonic series for the flow of each cylinder is converted to pressure pulsation at cylinder nozzles. Finally, the contributions of each cylinder are summed in amplitude and phase at level of piping system, connecting the cylinders (i.e., combined pulsation levels), while also considering possible different diameters of the cylinder single line and common stream piping. The calculation is done for all operating conditions, first for the generated pressure pulsation of each separate cylinder and then for the sum in phase of all the pulsation cylinders insisting in the common line. Finally, the worst value of combined pressure pulsations among all operating cases is selected.

Below is an example of the pre-study calculation for a 1st Stage Suction (Figure 4), related to a 10-cylinder compressor with five cylinders 72° phased (Table 1) on each side, and with the related crankshaft phase already enhanced (Figure 5).

The main characteristics related to hyper compressor cylinders are indicated in Table 1.

### Table 1: Suction hyper compressor data

<table>
<thead>
<tr>
<th>Cyl.</th>
<th>Effect</th>
<th>Phase deg</th>
<th>Bore mm</th>
<th>Clearance %</th>
<th>Stroke mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HE</td>
<td>108</td>
<td>100</td>
<td>28.1</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>252</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>&quot;</td>
<td>324</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>4</td>
<td>&quot;</td>
<td>36</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>&quot;</td>
<td>180</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

The calculation method takes all necessary data related to the design process and compressor directly from the compressor sizing program and only requires the introduction of a few additional pieces of plant data such as cylinder piping size and common pipe size.

If the thermo-dynamical parameter on common pipe is known at this stage it is possible to consider adjusting it. If the streams are further divided or combined, more than one common pipe of different size can be considered.

The results of the calculations are specifically related to the various conditions (Table 2). The outline of the calculations indicates the values on the critical areas.

### Table 2: Pulsation results evaluation at bid

<table>
<thead>
<tr>
<th>Cond</th>
<th>At cylinder nozzle</th>
<th>Common line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residual pulsation</td>
<td>Residual pulsation</td>
</tr>
<tr>
<td></td>
<td>(p.p. %)</td>
<td>(p.p. %)</td>
</tr>
<tr>
<td></td>
<td>Main Harm (p.p. %)</td>
<td>Main Harm (p.p. %)</td>
</tr>
<tr>
<td>01</td>
<td>1</td>
<td>5.05</td>
</tr>
<tr>
<td>02</td>
<td>1</td>
<td>3.89</td>
</tr>
<tr>
<td>03</td>
<td>1</td>
<td>5.17</td>
</tr>
<tr>
<td>04</td>
<td>1</td>
<td>4.90</td>
</tr>
<tr>
<td>05</td>
<td>1</td>
<td>3.81</td>
</tr>
<tr>
<td>06</td>
<td>1</td>
<td>3.87</td>
</tr>
<tr>
<td>07</td>
<td>1</td>
<td>5.03</td>
</tr>
<tr>
<td>08</td>
<td>1</td>
<td>3.89</td>
</tr>
<tr>
<td>09</td>
<td>1</td>
<td>5.18</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>3.81</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>4.90</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>3.81</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>1.79</td>
</tr>
</tbody>
</table>
Additional detailed information on the pulsation level of critical areas also can be diagrammed (Figures 6A, B, C, and D).

The summary of the residual pulsations with an endless line derived from Table 2 are:

- Max Unfiltered Pressure Pulsation at Cylinder Flange = 5.67 percent (percent p.p) (5.18 1st)
- Max Unfiltered Pressure Pulsation on Common Line = 1.14 percent (percent p.p) (.76 percent 5th)

Note that at least a 30 percent margin for plant acoustic resonance amplification can’t be fully mitigated by orifices.

The bid stage evaluation results confirm that a combination of the five cylinders (line 6") 72° phased into a common stream (line 8") is very effective in drastically reducing (i.e., from 5.67 to 1.14 percent peak to peak) the unfiltered residual pulsation on the common line. There also is a similar reduction for harmonic spectrum component amplitudes (i.e., from 5.18 of 1st harmonic to 0.76 percent of 5th harmonic). Also, in this case, the values detected are very good, even though there is possible partial amplification (e.g., 30 percent increases) due to real plant resonances that can’t be fully reduced by orifices.

Therefore, no further evaluation is necessary. If the result is higher than the desired value, the calculation is repeated, changing the diameter, or if applicable, changing the cylinder connections, to provide immediate feedback to the customer. At this point, the relevant pipe size can be used for preliminary cost estimation.

Order Execution

This simplified approach, neglecting the effect of the length (i.e., possible acoustic resonances) between the cylinders and the common lines, should be followed by a preliminary study to be performed right after the order, as soon as the first layout around the compressor is available or, at least, before the pipe order is issued.

It is particularly important to do this when the margin between the desired pulsation values and the above approximated bid values is small (e.g., below 30 percent), to assure that the reduced margin is still sufficient – thanks to the insertion of orifice pressure drops – to adsorb variation on the results attributable to the real plant resonance effects. This preliminary study helps ensure that the system layout is accurately represented during the bid stage evaluation (no misunderstanding is allowed on these fundamental aspects).
At the same time, since it’s happening in a very early stage of the project, the preliminary acoustic study should allow mitigation of issues that could arise from neglected aspects (e.g., additional operating conditions that were not studied/included during the bid phase) and provide additional critical data for a correct project design.

**Preliminary study at project start**

For these reasons, when the first real compressor layout, including the cylinder and stream connections up to the common lines (i.e., extracted from a real general arrangement) is available, the above evaluation should be checked by an actual preliminary pulsation study. The rest of the system, which isn’t available yet (e.g., equipment and interconnections), must be simulated by using reasonable assumptions (e.g., intercooler length used in similar applications). In this way the possible acoustic resonance amplifications are already evaluated, and only a fine-tuning and orifice enhancement probably are needed during the final acoustical study.

The scope of this preliminary study is to verify the:

- Suitability of the pipe lengths around the compressor
- Approximate real residual pressure pulsation
- Approximate pulsation-induced forces
- Amount of pressure drop (orifices size) necessary to achieve the above

Because they include possible acoustic plant resonance amplification, the pulsation values resulting from this study are generally higher than what had been evaluated previously at the bid stage. When the bid stage evaluation yields fully acceptable results (i.e., below 70 percent of allowable), this study also usually yields results that are fully acceptable or just slightly exceed what can be accepted after the evaluation of the relevant induced forces.

For the same application noted above for the bid evaluation (Table 2), the following results are obtained once the necessary orifices are inserted:

- Lengths around the compressor are acceptable.
- Approximate real residual pressure pulsations obtained are in line with those calculated during the bid.

### Table 4. Preliminary study results after bid evaluation

<table>
<thead>
<tr>
<th>Location</th>
<th>Unfiltered value (p. to p.)</th>
<th>Main harmonic components (p. to p.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common line</td>
<td>1.5%</td>
<td>5th, 0.85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10th, 0.33%</td>
</tr>
<tr>
<td>Cylinder flanges</td>
<td>7.2%</td>
<td>1st, 5.66%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2nd, 3.25%</td>
</tr>
</tbody>
</table>

The calculations are within reasonable values. The maximum pulsation induced forces around cylinders and on common line are approximately 700 Kg zero-to-peak. In proximity to the cylinders, these forces result from the relevant high pulsations and are contained by few supports, as they are found in the first few meters of piping with elbows. However, in the common line, these high forces are contained by several supports (i.e., they can be found only between two elbows at several meters where the pulsation is in counter-phase) so they usually are only a problem when located on elevated structures (e.g., attention should be paid to the structure stiffness for the intercooler of pre-heater).

- The amount of orifice pressure drop resulting from the pulsation of hyper compressor suction that’s necessary to achieve the above is 1.3 percent. For this kind of application, that is considered acceptable, based on experience.

At this stage, all necessary evaluations on the above-mentioned fundamental data are available, along with possible additional recommendations in case the customer wants increased improvement in plant behavior. Immediately after the preliminary acoustical analysis results are known, the customer can make final orders for piping, valves and fittings, in most cases with the same pipe size used during the bid.

**Final acoustical study**

When all of the information necessary to perform the acoustic study is available in a frozen status, usually in a late stage of the project, the actual acoustic model is updated and the study is performed, starting from the assumptions made during the preliminary evaluation and recommendations.

At this stage the most frequent and simple remedy adopted during this final check is the use of orifices (Figure 7). The reduction of the wave amplitude is obtained by inserting a damping effect, which is a function of the pressure drop: the higher the pressure drop, the higher the damping. In fact, the damping efficiency increases proportionally with the drop in pressure, which is determined by the square of the instantaneous gas velocity through the orifice. The orifice positions are selected so that the predominant harmonics are damped out. To achieve maximum effectiveness, an orifice should be located in the piping sections where the gas velocity is the highest in the standing wave field of the resonance. The standing wave field is the sum of several harmonic components, each with a certain frequency, module and phase. The ideal position will be identified by fine-tuning trials, with the aim of damping as many harmonic components as possible [6,9].

![Figure 7. Orifice for high pressure](image-url)

If the first two steps are correctly executed, this last check will only require orifice adjustments for location and pressure...
drops that usually remain within previously estimated ranges. However, if the preliminary check is avoided and the study is performed only when the information is complete (i.e., usually in an advanced phase of the project) it might become difficult or even impossible to apply modifications to the piping layout.

At that stage, if high-pressure pulsations and relevant forces are detected, the only remaining system design enhancement methods available to the designer are the use of orifice pressure drops, piping supports and structures stiffening.

Considering the cost of this type of application, the safety implications and efforts that might be necessary to mitigate adverse pulsation phenomena, the risk of leaving the analysis to the final stage is too high. On the other hand, the cost of the aforementioned additional bid evaluation and preliminary study is negligible compared to the benefits obtained in all other design aspects, such as plant operability and reliability.

Of course, the mechanical study design and verification must proceed in parallel or sequentially with the acoustical analysis to support the complete plant design.

Mechanical Analysis

Piping vibrations and cyclic stress

The mechanical study investigates the natural frequencies and the forced response of the plant, to keep vibration amplitudes and stresses within allowable limits. This is achieved, first, by defining the number and position of piping supports so that the mechanical natural frequencies are separated from the most significant exciting frequencies [6, 8, and 9]. Guidelines based on experience with similar applications can lead the initial mechanical design. These guidelines prevent significant modifications that otherwise would emerge from the final mechanical analysis. Typically the guidelines set the allowable values of [6]:

- Minimum piping mechanical frequency
- Maximum force applicable at each support
- Maximum span between two consecutive supports
- Minimum support stiffness of piping support, depending on piping size

In general, high mechanical natural frequencies lead to better mechanical behavior; therefore, the design should enhance the overall stiffness and reduce improperly supported masses.

Here are some practical recommendations in this regard:

- Piping should be placed as close as possible to the ground for easier application of stiff supports.
- Concentrated masses such as elbows, tee joints, valves etc. should be adequately supported.
- Supports and supporting structures should be much stiffer than supported components.
- An axial constraint should be provided for any straight pipe sections to contrast axial shaking forces.

The piping induced forces (shaking forces), determined by the pressure pulsations analysis, are automatically introduced as input data for the final mechanical tuning of the plant.

The mechanical analysis of the piping system is performed by a proprietary program that provides the mechanical frequencies, the total vibration amplitudes and relevant stresses, along with the reactions at support locations [8].

Mode shapes and associated natural frequencies are determined by means of a Finite Elements Method. Then, the overall forced response of the piping system is calculated, using the technique of “modal super-imposition” as the sum of the response of each mode to the exciting harmonics, each with its module and phase. For a system having N degrees of freedom the response to harmonic excitation is given by formula (2):

\[
x_k = \sum_{n=1}^{\infty} \frac{D_{kn} F_n}{\omega_n^2 m_n} \frac{1}{\sqrt{1 - \omega^2/\omega_n^2}} \sin(\omega t - \theta_n)
\]  

(2)

Once the total response of the piping system has been calculated for vibration amplitude, the relevant stress is also obtained. The procedure explained in ASME VIII-2 appendix 5 [2] is applied to calculate the maximum alternate stress. The stress is compared with the allowable cyclic stress limit to verify its suitability. In this phase, the dynamic behavior of the complete piping system (branches, rigid or flexible supports, concentrated masses, simple supporting structures, etc.) is investigated.

If needed, a combination of additional orifices and/or supports is selected to reduce the overall impact on plant cost and performance [9]. In general, when the initial guidelines are correctly followed, very limited modifications are required during this enhancement phase.

Cylinder manifold investigation

The same kind of analysis can be made of the compressor frame itself through an FE model, including the cylinders and connected piping till the ground and the relevant supports, using the following input exciting forces [5]:

- Acoustic pulsation induced forces
- Cylinder gas forces applied at cylinder ends and crankshaft
- Dynamic forces acting on the foundations because of centrifugal forces of the rotating mass

To be effective, the model should include a very accurate representation of the compression system (i.e., derived from a 3D translation of the manufacturing model) (Figure 8).

Figure 8. FE cylinder manifold model
Such a model that considers all forces acting on the compressor (i.e., not only the pulsation induced forces) can identify possible vibration issues around the compressor that can’t be predicted by standard piping vibration study.

Using the same procedure previously described for the piping can determine the system vibrations and cyclic stress and identify any necessary modifications [12, 13]. Usually, these modifications are adjustments of the piping supports and relevant supporting structure stiffness around the compressors.

**Intercooler and tubular reactor**

The same kind of analysis used for the piping system can be applied to the intercooler and reactor structures (Figure 9) to verify that they can maintain vibrations and cyclic stresses within allowable limits [9].

**Figure 9. Intercooler FE model for dynamic response**

Considering the high cost of this equipment, the experience of the manufacturer and designer may not be sufficient to avoid vibration issues. Therefore, even at an additional cost, a dynamic study should be conducted, especially for equipment size or operating parameters involved with new applications [12].

**Conclusions**

LDPE production in large-scale plants requires processing equipment with larger capacities, including the use of reciprocating compressors. Plant design must create a safe and reliable operation, since that is critical to end users’ and suppliers’ success.

Past experience, best practice guidelines and preliminary acoustic analysis should drive the project’s development. Since compressor components such as reactors and intercoolers operate at high pressures and have very long delivery times, the piping size selection requires careful analysis at an early stage to estimate the costs properly. At the bid stage, the compressor requirements are already known, while the plant layout, except for standard applications (e.g., carbon copy of a previous plant), is only defined in a late stage of the project.

New programs are available to calculate the approximate combined pressure pulsation generated in the common endless line during bid stage. These programs just use P&I diagram data and a simplified pre-calculation routine linked to compressor program sizing that accounts for plant thermo-dynamical data.

Next, the harmonic series for the flow of each cylinder is converted to pressure pulsation at cylinder nozzles. The calculation is done for all operating conditions, starting with the generated pressure pulsation of each separate cylinder and then doing the sum in phase of the cylinders insisting in the common line. Finally the worst value of combined pressure pulsations among all operating cases included in the data sheet is selected.

Based on these results and the selected cylinders’ connection arrangement, a suitable piping size can be chosen to estimate piping size cost.

Before the pipe is ordered, and based on the first real layout around the compressor and almost frozen operating conditions, the above evaluation must be confirmed by a preliminary pulsation study that avoids introducing any changes that could alter what was evaluated during the bid stage (e.g., additional operating condition or changes to the connections among the cylinders).

The final acoustical and mechanical studies will indicate the necessary improvements, which generally are minimal, to achieve delivery target and proper operation.

This approach requires strong cooperation among the compressor manufacturer, equipment manufacturer, end user, engineering contractor and vibration specialists, since they will be involved in collaborative decision-making during the design process.

Only a depth static and dynamic design, from the bid stage to the final layout, can establish the cost-effective performance, reliability, and availability of the whole plant.
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Reciprocating compressor cylinder’s cooling: a numerical approach using computational fluid dynamics with conjugate heat transfer

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