Pressure Pulsations Generated by Centrifugal Pumps

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Foreword

With the introduction of increasingly higher speed papermaking machinery, it became increasingly important to use pumping equipment which exhibits low pressure pulsation characteristics in the associated hydraulic system. If pressure fluctuations are excessive at the inlet of the headbox, "barring" becomes apparent in the sheet of paper. This unevenness in the paper thickness cannot be tolerated if proper papermaking operations are to be maintained.

Along with new requirements for pumping machinery, there appeared new terms dealing with pressure pulsations which, to many, were unfamiliar. The following paragraphs of this article will not only acquaint the reader with terminology related to pressure pulsations, but will also describe some of the characteristics and methods of controlling/minimizing pressure pulsations. Additional topics covered include instrumentation and techniques/methods used to measure pressure pulsations.

Pressure Pulsations

Pressure pulsations are fluctuations in the basic pressure/head being developed by the pump. These pulsations can sometimes be very severe and cause damage to the piping or other components in a hydraulic system. However, in some cases, as in modern papermaking systems, even apparently minor pressure variations cannot be tolerated because of their detrimental effect on the operation of certain equipment in the system, primarily the headbox. Obviously then, the severity of pressure pulsations cannot be determined merely by their presence or even magnitude, but rather by their effect upon system components or operations.

There is no pulseless pump. Regardless of the type, all pumps have pressure pulsations to some degree because of changes, discontinuities and/or variations that occur in their pumping or pressure generating action. A single acting reciprocating pump is a good example of discontinuity in pumping action. When the plunger reverses direction at the end of its discharge stroke, there is a cessation of pressure generation for the duration of the return or suction stroke. During this time, the discharge pressure decreases until the next discharge stroke occurs. This form of pumping action results in a pressure pulsation of significant magnitude.

In a centrifugal pump a pressure pulse is developed as each rotating vane passes the cutwater or diffuser vane reaching a maximum value when the vane tip passes this point. When the vane tip is adjacent to the cutwater, the maximum amount of energy in the form of liquid in motion is directed toward the discharge nozzle. At any other point between vane tips, the opening between the vane and cutwater is larger and, consequently, some of the liquid (and inherent energy) "slips by" under the cutwater and is recirculated through the pump. The change from minimum to maximum transfer of energy to the discharge nozzle results in a corresponding change or variation in the discharge pressure which constitutes a pressure pulsation. The magnitude or, as it is commonly called, the amplitude of the pressure pulsation is directly related to the amount of difference between the maximum and minimum "slip," or the distance between the impeller vane tips and the cutwater.

Pressure pulsations have two important characteristics: frequency and amplitude. Both of these must be known in order to evaluate and solve pulsation problems.

Frequency

Frequency is defined as the number of recurrences of a periodic phenomenon in a unit of time, e.g. revolutions per minute, cycles per second, etc. In the case of pressure pulsation measurements, of primary interest is the number of pulses occurring per second. Although pulses per second is more descriptive of the phenomenon, hertz, which is cycles per second, is the commonly used term.

The vane frequency is the basic frequency generated by a centrifugal pump. As stated previously, there is a pulse generated each time a vane tip passes the cutwater. If there are seven (rotating) vanes in the impeller and one (stationary) cutwater, for each complete revolution of the impeller seven vane tips pass the cutwater or there would be seven pulses per revolution. If it took one second for the impeller to complete one revolution, the vane passing frequency would be seven hertz. The equation for determining the impeller vane passing frequency is:

$$f_{IVP} = N_{iv} \left(\frac{S_{iv}}{60}\right) \text{ where}$$

f_{IVP} = Impeller Vane Passing Frequency (hertz)

N_{iv} = Total Number of Vanes in the Impeller

S_{iv} = Speed of the Impeller (revolutions per minute)

The above equation is used to determine the basic pulsation frequency for a single cutwater pump. If there is more than one cutwater (or if the pump has diffusers), each impeller vane will pass each (stationary) cutwater as it rotates, generating a pulse each time. Obviously, the equation must take into account the additional stationary points. For example, in a dual volute pump with two cutwaters, each impeller vane would pass a (stationary) cutwater twice for each complete revolution, thereby generating two pulses per revolution. For a particular impeller with an *odd number* of vanes, this would result in a vane frequency that is two times higher than what it would be with a single volute pump. If in the example the impeller contained an *even number* of vanes, regardless of whether the pump had a dual volute or single volute, the frequency would remain the same. This is because, with an even number, impeller vanes would be diametrically opposite and, as the cutwaters are also diametrically opposite, two impeller vanes would be adjacent to the two cutwaters at the same time. Therefore, both impeller vanes would generate a pulse at the same time. Although in this instance the frequency is not altered with a dual volute, the magnitude of the pressure pulsation would be greater than what it would be with the same impeller in a single volute pump. For this reason, an odd number of impeller vanes should always be considered in a dual volute pump.

With a diffuser pump, because there are many stationary points to consider, the situation becomes more complex; and it becomes somewhat more difficult to avoid having more than one impeller vane and cutwater or diffuser adjacent at any one time. Simply choosing an odd number of impeller vanes no longer proves satisfactory in all cases. As a rule, it is best to choose values which are prime numbers and different for the impeller and diffuser vanes. With a diffuser pump or any multiple cutwater pump, the basic impeller vane frequency is referred to as the vane rate frequency and the equation for calculating this frequency is:

$$f_{IVR} = \frac{N_{iv} \times N_{dv}}{C_F} \left(\frac{S_{iv}}{60}\right) \text{ where}$$

f_{IVR} = Impeller Vane Rate Frequency (hertz)

N_{iv} = Total Number of Impeller Vanes

N_{dv} = Total Number of Diffuser Vanes

S_{iv} = Speed of the Impeller (revolutions per minute)

C_F = Highest Common Factor of N_{iv} and N_{dv}

Amplitude

The amplitude of a pressure pulse is a measure of the maximum amount by which the pressure varies from the average or steady-state value. The amplitude may be expressed in various ways. A common unit of measurement is pounds per square inch (psi), peak-to-peak, which represents the total pressure variation. The amplitude can also be expressed as psi, peak, or psi, root-mean-square (rms). The latter term is also referred to as the effective value because it represents the value of a varying condition which is equivalent to a steady-state condition. All of these terms are mathematically related, and it is a simple matter to convert from one to the other. Figure 1 illustrates graphically and mathematically the relationship between all three terms.

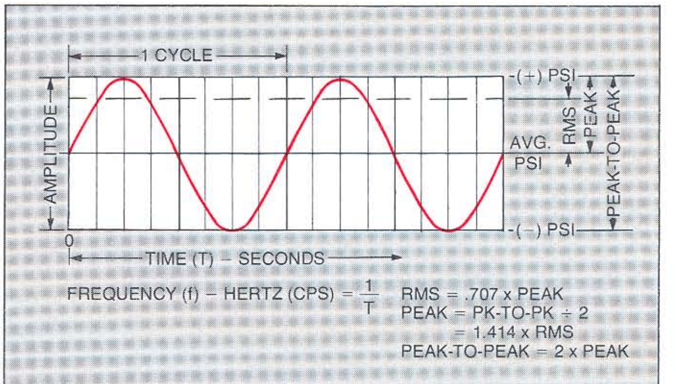

FIG. 1 — Illustration of terms relating to amplitude measurements

Another unit used in measuring the magnitude of pressure pulsations is the decibel (dB) or more specifically the pressure decibel (pdB). The decibel is a dimensionless unit expressing a logarithmic ratio between two quantities, one the measured quantity, the other a reference quantity. When measurements are made in decibels instead of amplitude, the term pressure level is used. Mathematically, the pressure level is defined as:

$$\text{Pressure Level (pdB)} = 20 \text{ Log}_{10} \frac{\text{Measured Pressure}}{\text{Reference Pressure*}}$$

*The reference pressure *must* be stated whenever a pressure level in decibels is given. The most common reference pressure is 0.0002 dynes per square centimeter (RMS) which is equivalent to 8.2×10^{-9} pounds per square inch (peak-to-peak).

The decibel scale is extremely convenient when analyses cover a wide frequency range. Normally in this situation, a large variation in pulsation amplitudes are encountered. Because the decibel scale is logarithmic, it is possible to record these variations in a compressed form, thereby eliminating or at least minimizing the number of scale factor changes that must be made. For example, a 60 decibel scale would cover a 1000:1 range of variations in amplitude. In most cases, this should be adequate to permit analysis from 0 - 1000 hertz using a single level scale factor throughout.

Factors Influencing Frequencies

In a *perfect* centrifugal pump, the vane frequency (vane passing or vane rate) and most probably harmonics (multiples) of it are the only discrete frequencies that would be generated. It is imperfections in the pump that generate additional discrete frequencies.

As evident in equations (1) and (2), the vane frequency can be changed by changing the number of vanes (impeller and/or diffuser) or the speed. Increasing (or decreasing) the frequency will not necessarily change the pulsation amplitude of the pump, but higher frequencies are attenuated, or absorbed, more rapidly by the system and, therefore, do not travel as far. Because of this, equipment located downstream of the pump will be less affected. Obviously then, in order to benefit from a vane frequency change, it would be necessary to increase the frequency.

When considering an increase in the number of impeller vanes to increase the frequency, a sacrifice in the pump's performance characteristics must be acceptable. It is very common for pumps using "multi-vane" impellers to exhibit a drooping characteristic toward shut-off in the head/capacity curves. This same characteristic is sometimes evident in diffuser pumps. Pulsations at the rotational frequency (recurring once per revolution) will appear due to inaccuracies in the impeller's geometric symmetry or concentricity. For instance, if the core shifts while casting an impeller, the hub would be off center in relation to the vanes and outside diameter. This would give the impeller a lobal characteristic and would cause the basic vane frequency to undulate at a rate equal to the rotational frequency. (See Figure 2.) Because the rotational component is a low frequency, especially in low speed pumps, it will not be easily attenuated by the system and could, therefore, affect other equipment located downstream of the pump. In today's high speed papermaking systems, pulsations at low frequencies can be detrimental to the operation in the form of barring or irregular paper thickness.

Except for the rotational frequency, pressure pulsations commonly appearing in the low end of the frequency spectrum are mostly due to the turbulence that is present in a flowing liquid, especially when flowing through and against rough and/or irregular surfaces. This phenomenon is commonly referred to as "flow noise." The appearance and amplitude of these discretes are very random in nature and in most cases do not cause problems.

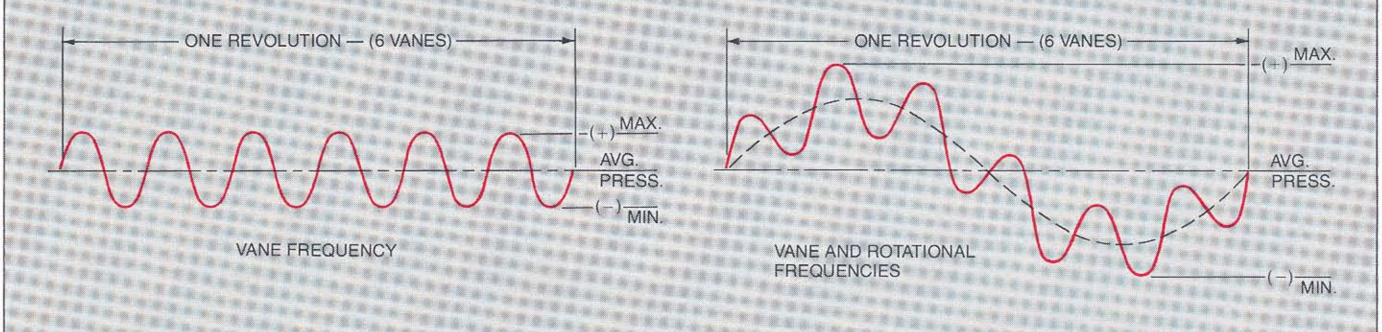

FIG. 2 — Waveforms showing basic vane frequency (6 vane impeller) and vane frequency plus rotational frequency

Control of Pressure Pulsations

Pumps considered for low pulse level applications must be selected, designed, constructed, and manufactured with much greater care than what might be expected for units intended for other applications.

When selecting a pump, it should be sized so that operation will be at or near its best efficiency point (b.e.p.). Operation at flows above this point should always be avoided because of the possibility of even slight cavitation influencing the pulsation levels. Operating the pump at flows below the b.e.p. is not as critical and should not present problems unless the deviation is extreme. Although it is difficult to establish a definite number for the allowable deviation while maintaining the pump's low pulse integrity, operation should be consistent with that required to maintain good overall performance characteristics. The impeller diameter is another item that must be considered. The greater the impeller vane to cutwater clearance, the lower the expected pulse level at the vane frequency and most likely other frequencies associated with the impeller including the rotational frequency. This is because the increased ''cushioning effect'' with a greater clearance decreases the effects of inherent impeller imperfections. When a choice exists, the smallest diameter with a higher speed is the most desirable selection.

The areas of concern discussed above must also be considered in the design and construction stages. However, because it is the most important item contributing to pressure pulse generation, the impeller must be given particular attention. In its design, the maximum possible number of vanes should be considered, but keeping in mind the ''drooping'' characteristic. The higher number of vanes will increase the vane frequency; and also, individual discrepancies would be less noticeable because, with a greater number of vanes, each individual vane would have less influence on the total effect. An odd number of vanes should be used. (However, with a split and staggered vane impeller this factor would not be important.) The impeller should be split with the vanes staggered and skewed, if possible. (See Figure 3.)

Finally, for the low pulse level pump, manufacturing methods which will insure superior geometric accuracy of the entire pump must be used. Again, the impeller is the key component to consider. A totally fabricated impeller would yield the best geometric accuracy. However, this would also be a very costly procedure. A more practical substitute would be to use accurate casting methods together with thorough inspection procedures. The cast impeller should be carefully inspected for geometric accuracy both before and after machining. Items such as vane spacing and concentricity must be checked carefully and irregularities of any kind must be corrected. Enclosed impellers should be cast minus the front shroud(s) to permit close examination of the entire vanes and inside of the impeller. The shroud(s) would be cast as a separate piece and later attached, after thorough inspection and evaluation of the impeller itself. As a final and important step, the completely assembled impeller must be dynamically balanced to a ''precision'' degree to minimize vibration and radial runout during operation.

As for the remainder of the pump, all hydraulic passages should be smooth to minimize turbulence. When split casings are used, the insides of the two parts must match at the parting flange. Gaskets between the parting flanges must be cut and installed accurately so that they do not protrude and interfere with the flow.

The Warren ''ACC-U-FAB'' impeller is a field-proven (cast) impeller designed and fabricated specifically for low pulse applications. Many paper mills in the United States and Europe are using this impeller in fan pumps and as a result are not experiencing any pump-related pulsation problems in their papermaking systems.

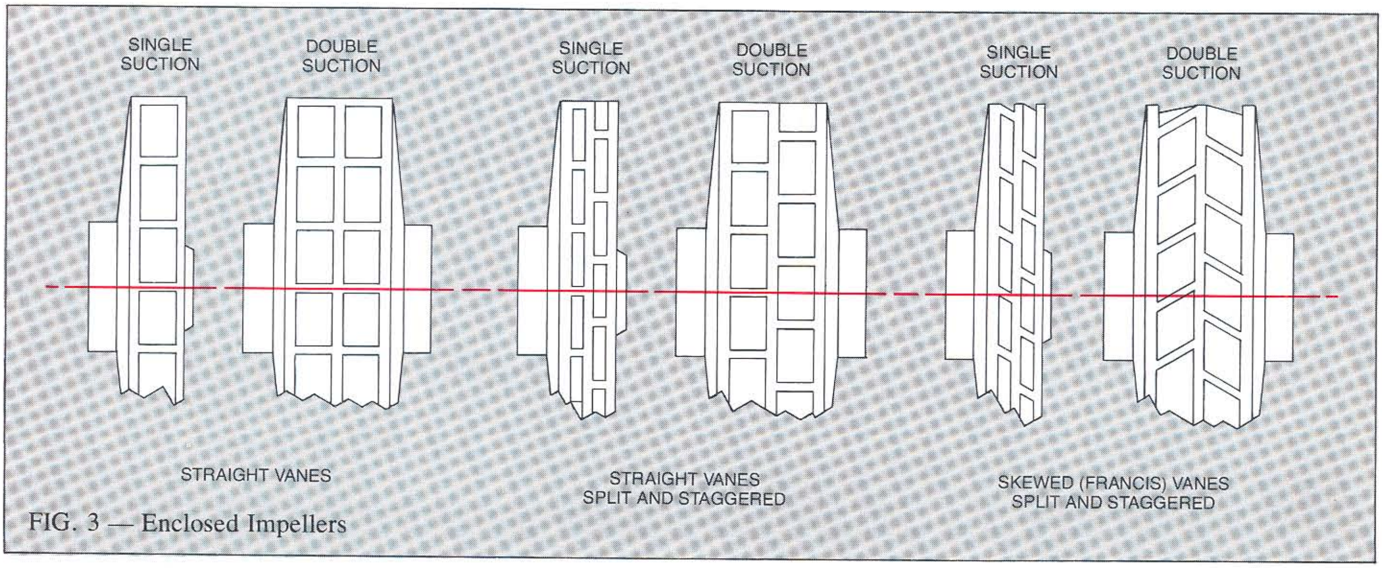

FIG. 3 — Enclosed Impellers

Test Instrumentation

The basic instruments required to obtain pressure pulsation data are a pressure transducer and a frequency analyzer. Although these two items are the basic requirements, additional instruments such as an amplifier, for boosting the output of the transducer, and a recording device, which will provide a permanent record of the analysis, are included in the system. A block diagram of a practical pulsation measurement system is shown in Figure 4. The following paragraphs discuss each of these items.

Pressure Transducer

This device is used to change pressure variations into voltage or current variations which can then be processed by the electronic instruments in the system. The output of a pressure transducer is a complex electrical signal representing a summation of the various individual pressure pulsations acting upon its sensing element.

There are various types of pressure transducers, each having its own advantages/disadvantages. Some of the more common types are the strain gauge, capacitance, variable reluctance and piezoelectric pressure transducers, and the hydrophone. The primary difference between them is in their sensing element.

When selecting a transducer, the most important qualities to consider are frequency response, sensitivity, and ruggedness. The frequency response must be flat over the range of interest. Usually, 0 - 1000 hertz is adequate for pulsation measurements. The sensitivity to pressure variations (volts-output/psi-excitation pressure) should be high, while the sensitivity to temperature changes and vibration must be low.

Amplifier

An amplifier is used to increase the relatively low level output of the transducer to a higher, more usable value. This permits a greater physical separation of the analyzing system from the transducer which would be desirable in cases where the measurement location is in an environment which might be harmful to the delicate electronic instruments. Another very important function of the amplifier is to provide an impedance match between a high (output) impedance transducer and the relatively low (input) impedance of the analyzer. An impedance mis-match would degenerate the low frequency response of the system.

Analyzer

Measuring the output of the pressure transducer directly would only indicate the overall amplitude or level of the pressure pulsation, but little or nothing would be known about the frequencies comprising this complex signal.

A frequency or spectrum analyzer, in addition to measuring the overall level, indicates the frequency and amplitude of each discrete element within the complex spectrum. Through this analysis, it is possible to evaluate the various machinery components in a system. By comparing the frequencies of the spectrum obtained through analysis to the frequencies generated by individual machines, offensive equipment can be identified.

There are a great number of analyzers available today which can be used for pressure pulsation measurement and analysis. The choice among them should be generally determined by individual requirements for frequency range of analysis, frequency resolution (the ability of the analyzer to distinguish between closely spaced frequencies), speed of measurement and the desired output format. Of these, frequency resolution should be given the most attention in order to obtain maximum capability for describing the frequency spectrum, thereby allowing a greater identification of the source(s) of pulsations. The frequency resolution of an analyzer is directly related to the bandwidth. It must be noted that a greater resolution, hence narrower bandwidth, requires a longer analyzing period to prevent a loss of data. In cases where a short analysis time is important, some sacrifice in resolution may be required. However, some of the more recent real-time spectrum analyzers can overcome this problem. Using modern digital techniques, these instruments can perform extremely high resolution analysis in a relatively short time.

Recorder

This instrument is included in the system to obtain a permanent graphic record of the analysis. There are various types of recorders and in some cases they are part of or must be matched to the analyzers. Basically, this unit provides a plot of the amplitude or level versus frequency.

Magnetic Tape Recorder

This instrument can facilitate field testing when the object of the test is to gather information rather than troubleshooting on-site. Only the overall level (and a calibration signal to provide a reference level) is recorded when using a tape recorder. This data is later played back into an analyzing system for complete amplitude versus frequency analysis.

For troubleshooting, obviously the tape recorder would not give on-site results. However, it can be a useful addition to on-site testing by providing a permanent recording which can be used for further analysis after returning from the field. Essentially, it brings the machinery located in a remote area into the test lab.

Calibration

Prior to making pulsation measurements, the analyzing system *must* be calibrated in order to establish a reference level for the subsequent pulse data. This is usually accomplished by introducing a known voltage at a known frequency at a convenient level corresponding to the output of the transducer. The frequency of the calibration signal is not important, providing it is within the range of the instrument. However, 400 or 1000 hertz are generally accepted standards.

In some cases transducers, such as piezoelectric types, are incapable of being calibrated by the user and must be sent to the manufacturer for re-calibration. This should be done on a regular periodic basis or whenever the transducer has been subjected to unusual conditions or treatment. When calibration of the transducer is possible, it should be included in the calibration to establish the reference level.

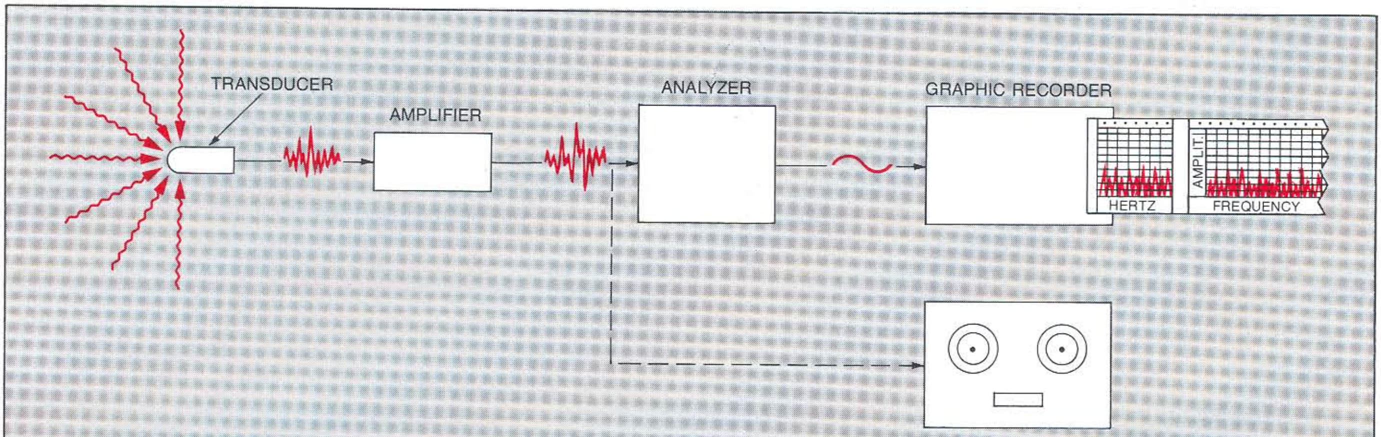

FIG. 4 — Block diagram of a typical pulsation measuring system

Testing Procedure

In making pressure pulsation measurements, the transducer must be located at a point in the hydraulic system which will most likely represent the pulsation amplitudes generated by the equipment being evaluated. The presence of standing pressure waves in a resonant system and the effects of piping components, fittings, valves, and the piping configuration itself all can influence the pulsation amplitudes and frequencies. Locating the transducer as close as possible to the discharge of the equipment under test should minimize the system's influence. A good rule of thumb is to keep the transducer within two feet of the discharge flange. Also, as long a straight run of pipe as practicable should follow the transducer.

After the measurement point has been selected, the transducer must be installed in a manner such that it does not protrude into the flow stream as this can also influence test results. Mounting the transducer flush with the inside pipe wall is ideal and easily accomplished in shop tests. However, field measurements are generally performed on operating equipment which cannot be shut down to install, and later remove, pressure transducers. In this case, at some convenient time, a valve is installed at each measuring point and can later be used for inserting the transducer into the system. The valve should be located as close to the pipe as possible and should be a type which is straight through when open, e.g. a gate valve or a ball valve. It should also be of sufficient size

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