LOSING THE LOSS COEFFICIENT

James R. Hardin, Elliott Group, USA, evaluates methods for analysing aerodynamic losses in downstream turbomachinery.

Aerodynamic losses have an important effect on the performance of any turbomachine. Consequently, people often want to measure the loss coefficient through a turbomachinery component. However, measuring the loss coefficient is much more difficult than it appears at first glance, and is sometimes even impossible. This article describes the challenges of measuring the loss coefficient in a centrifugal compressor inlet, using computational fluid dynamics (CFD) to evaluate measurement techniques.

Background

Total pressure is the pressure that would result from bringing a fluid to a stop isentropically, that is, with no losses. It is the sum of the static pressure (the actual pressure of the fluid) and the dynamic pressure (the effective pressure caused by the movement of the fluid). The loss coefficient for a component equals the drop in total pressure divided by the difference between incoming total and static pressure.

$$Loss\ coefficient = \frac{P_{total\_1} - P_{total\_2}}{P_{total\_1} - P_{static\_1}}$$

Station 1 is where flow enters the component, and Station 2 is where flow leaves the component. For an incompressible fluid, the denominator turns out to be 0.5(Density)(Velocity)^2 at Station 1, so loss coefficient is often written with that substitution. This is often an adequate approximation even for a

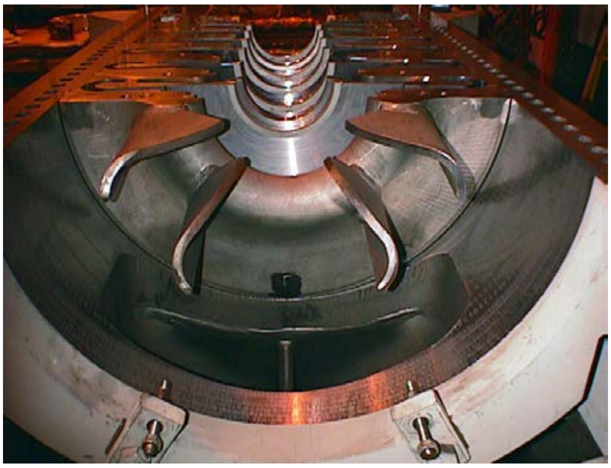

Figure 1. Compressor inlet half.

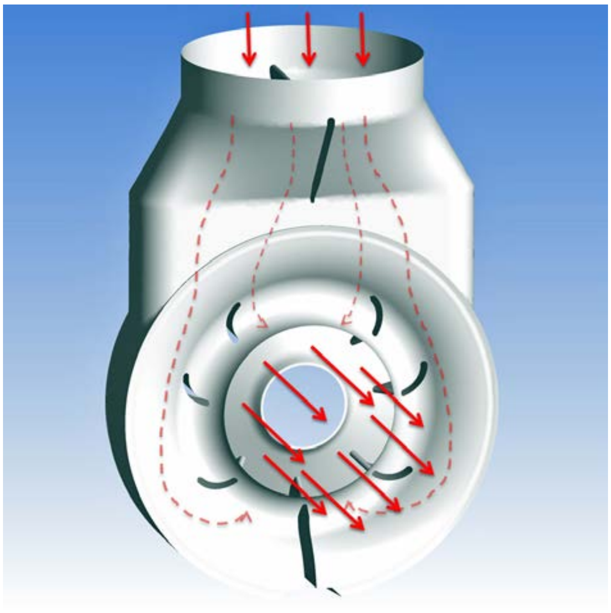

Figure 2. Inlet CFD model.

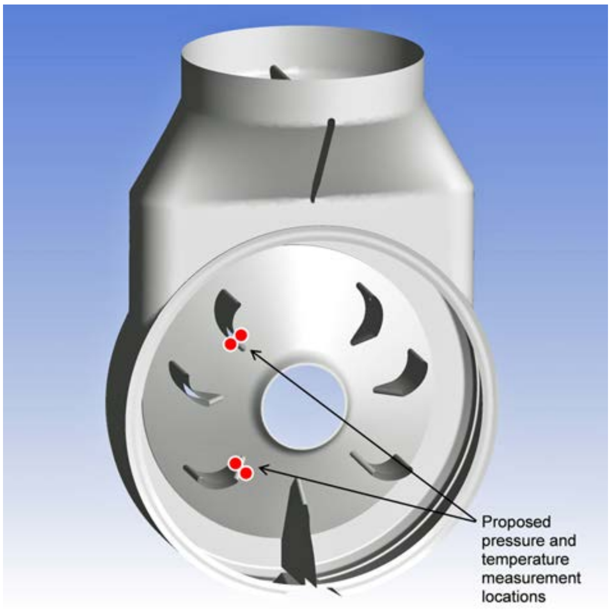

Figure 3. Instrumentation locations.

compressible fluid, as long as the velocity is low; therefore, density is nearly constant through the component.

The first challenge is that for a Station 1 condition with a low velocity, the difference between total and static pressure (the denominator) is small, making it difficult to measure accurately. For a compressor inlet, however, finding a good value for the discharge total pressure is even more difficult.

Compressor inlet example

Figure 1 shows half of a compressor inlet, looking downstream through where the endwall will be in the final assembly. Flow enters through the nozzle, visible at the bottom of the inlet, spreads out through the vanes, and continues downstream through an annulus to the first impeller.

Figure 2 shows a similar inlet as it appears in a CFD model. It has been turned over so flow enters from the top instead of the bottom, and the view is looking upstream instead of downstream. The red arrows show how flow proceeds through the inlet. The figure may look strange to anyone not accustomed to CFD modelling because of typical idiosyncrasies such as:

- Some surfaces are removed to enable a reader to see inside the part, resulting in a view of the assembly that could never exist in real life. For example, the shaft is not present, and the casing downstream of the inlet has been removed.
- Only surfaces that contact the flowing gas are shown. For most CFD models, where mechanical and heat transfer effects are not included, these are the only surfaces that exist in the model. The CFD analysis does not know or care about the actual solid pieces that these surfaces are part of. Consequently, one can see right through the vanes, and the overall geometry seems misshapen because the outer surfaces of the casing and nozzle are missing.

Trying to find total pressures

In a test, total pressure can be measured with probes that protrude into the flow and capture some fluid, bringing it to a stop with low loss. The probes must be aligned with the flow direction within some tolerance. Another common approach is to measure the static pressure with static taps and calculate the total pressure from known fluid conditions and geometry. The process is as follows:

1. Measure static pressure (P).
2. Measure static temperature (T).
3. Find density (ρ) from gas properties.
4. Calculate velocity ($V = w/(\rho A)$, where w is mass flow and A is flow area).
5. Calculate total pressure: $P_{total} = P + (\rho V^2/2)$.

Instrumenting the pipe near the nozzle inlet flange is not difficult, and because of the uniform flow coming from a straight inlet pipe, a measurement should give a good approximation of the mass-averaged

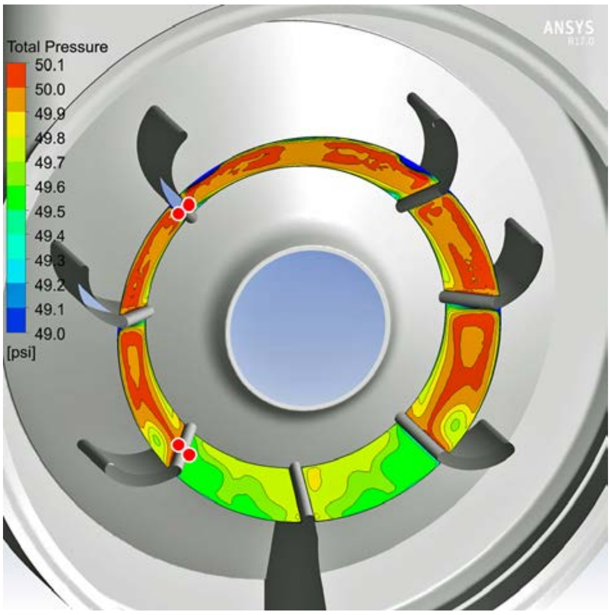

Figure 4. Total pressure near vane trailing edges.

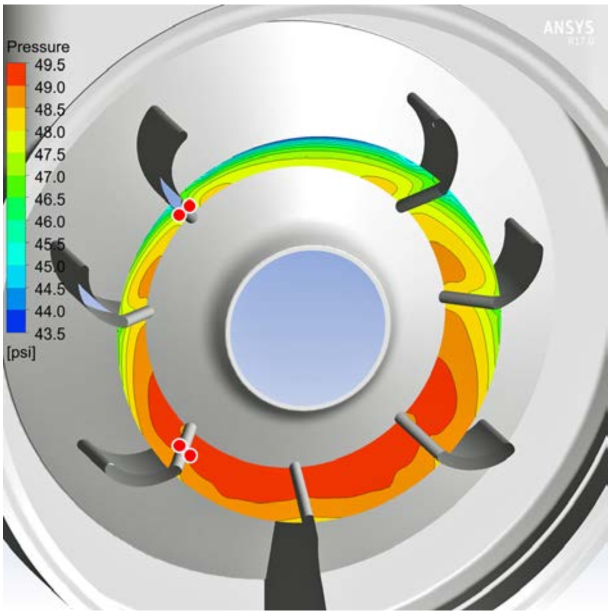

Figure 5. Static pressure near vane trailing edges.

value across the entire pipe. CFD can confirm this by sampling flow parameters at instrument locations. Using static pressure and density values along the outer edge where pressure taps would be yields a total pressure value of 49.993 psi for this particular case. Mass-averaging the total pressure across the entire pipe gives 49.994 psi, a difference of only 0.001 psi. Therefore, it can be assumed that the inlet conditions are well known.

Finding the total pressure leaving the inlet is more difficult. Pressure taps that measure the static pressure are often placed on the vanes near the trailing edges. In Figure 3, the inlet's shroud surface (part of the first diaphragm) has been removed to show the interior of the inlet. Red circles have been placed at possible locations for pressure taps, on the pressure and suction surfaces of two vanes near their trailing edges. If temperatures are taken nearby, density can be calculated at these locations. These values are often used to calculate total pressure, since installing total pressure probes is often impractical in a shop floor test.

Figure 4 shows the total pressure across the entire flow passage near the trailing edges, something only CFD can reveal. Total pressure is non-uniform, with lower values opposite the nozzle. Consequently, measurements taken on the suction side of the vane nearer the bottom would show lower total pressure, and thus a higher loss coefficient through the inlet. What is the average total pressure near the trailing edges? That depends on how it is calculated, and the difference can have a big impact on the calculated loss coefficient. The mass-averaged total pressure across the passage, a value that can only be found with CFD, is 49.852 psi. Calculating total pressure from test data is usually done by using the static pressure and density, along with the mass flow and flow area. Using mass-averaged values of static pressure and density (thus not considering the specific instrument locations), this approach yields a total pressure at the vane trailing edges of 49.152 psi, much lower than the mass-averaged CFD value. This difference in total pressure drop is enough to increase the calculated loss coefficient by more than a factor of five.

There are three main reasons for the big difference in calculated total pressures:

- The surface where the averages are taken is orientated parallel to the trailing edges, not necessarily being a true quasi-orthogonal for the flow passage. Consequently, the area might be too large, resulting in too small a calculated velocity, and thus too low a total pressure. Determining the area to use is a challenge for real tests, not just CFD, when total pressure is calculated from static pressure and mass flow.
- CFD calculates total pressure using the entire velocity at every node, not just the component perpendicular to the flow surface. Calculations using mass flow and area, by nature, use only the component of velocity perpendicular to the calculation surface, neglecting secondary velocity, and thus finding a lower total pressure. Which of the two approaches is correct depends on what happens downstream, and can lead to long debates among engineers.
- Mass-averaging total pressure is not exactly correct for finding an equivalent total pressure for a non-uniform flow field. There is no simple procedure to get a truly equivalent average total pressure.

Since one approach uses static pressure to calculate total pressure, the variation of the static pressure field, shown in Figure 5, should be investigated.

The trend is opposite that of the total pressure. The high velocity near the nozzle results in low static

Table 1. Fraction of inlet loss coefficient from static pressure at each pressure tap

Pressure tap location	Loss coefficient relative to value using mass-averaged total pressure
Upper vane, pressure surface	9.6
Upper vane, suction surface	10.6
Lower vane, pressure surface	-3.1
Lower vane, suction surface	-2.8
Average of the four locations	3.6

Table 2. Fraction of inlet loss coefficient from total pressure at each pressure tap

Pressure tap location	Loss coefficient relative to value using mass-averaged total pressure
Upper vane, pressure surface	3.7
Upper vane, suction surface	-0.1
Lower vane, pressure surface	4.2
Lower vane, suction surface	0.6
Average of the four locations	2.1

pressure. When calculating total pressure from static pressure and mass flow, however, the same average velocity is assumed for every point, so the calculated total pressure tracks with the static pressure. Consequently, using the pressure tap locations on the lower vane results in higher calculated total pressures than using those on the upper vane, despite the total pressure field shown in Figure 4. In fact, the calculated total pressure is higher than the inlet total pressure, leading to a negative loss coefficient.

Considering the difference in loss coefficients found even for full-passage averages above, it is hard to know what the 'right' answer is to compare. Table 1 shows loss coefficients calculated from static pressure at each of the possible pressure tap locations, using the loss coefficient from mass-averaged values of total pressure as a reference value.

The calculated loss coefficient ranges from about -3 times the reference value (three times the magnitude and negative besides) to more than 10 times the reference value.

Even if total pressure probes could be used, Figure 4 shows that locating them correctly would be challenging. CFD values of total pressure across the entire calculation surface vary from 45.287 to 50.179 psi. Depending on where a probe was placed, the loss coefficient could range from about -1 times the reference value (same magnitude but negative) to more than 33 times the reference value. Table 2 shows loss coefficients calculated from total pressure at each of the possible pressure tap locations, similar to Table 1, even though the selected locations would not be practical for total pressure probes.

Lose the loss coefficient

The best approach to finding the loss coefficient from testing is:

1. Calculate the best reference value of CFD-based loss coefficient, using mass-averaged total pressure across the entire passage.
2. Find instrument locations from the CFD results that give a representative loss coefficient value.
3. Check those locations with CFD runs at different conditions to make sure they still give representative answers.
4. Place instruments in the actual test in the locations determined from CFD.

Even this best approach is not very accurate. There may not be any practical instrument locations that give reasonable values of loss coefficient, and the optimum locations may vary as flow conditions are changed. Loss coefficient is very sensitive to small errors in total pressure simply because the total pressure drop through an inlet is so small.

There does not appear to be a reliable way to get accurate inlet loss coefficient measurements from a test, especially a shop test or field test. Fortunately, the exact value of loss coefficient does not matter very much. Calculations of section performance, which are what really matter, are far less sensitive to small variations in total pressure.

In this case, the calculated value of total pressure at the vane exit from averaging the static pressures at the four instrument locations is only 0.76% lower than the mass-averaged value. Using total pressures at the instrument locations gives a total pressure only 0.31% lower. So total pressure values calculated at the vane trailing edges of an inlet can be used to find the performance of a downstream section with little error.

To find the inlet's discharge total pressure for performance calculations, it is usually sufficient to start with the pressure in the inlet pipe and use the loss coefficient the original equipment manufacturer has found from analysis or better-controlled development tests. If the pressure is to be measured at the exit of the inlet, CFD can be used to locate instruments well enough to provide accurate section performance calculations. Do not use the measured loss coefficient for anything more than an order-of-magnitude check of reasonableness. For example, if the loss coefficient comes out negative, then ignore the measured inlet discharge pressures and work from the inlet pipe.

Asking how to get an accurate loss coefficient measurement from a shop or field test is asking the wrong question. The more important question is how to get accurate section performance data, and that question has a better answer. HE

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