Characterization of surge phenomenon by the temperature tracking in power plants turbochargers

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Abstract

A common technique to detect the surge phenomenon has been by means of monitoring the temperature in the compressor inlet duct. In the intake manifold, when the instabilities become intense, the temperature increases proportionally. This explains because the temperature gradients begin to appear before the surge phenomenon occurs and its magnitude depends to the compressor size, among others. Additionally, the temperature gradients have an important correlation with the noise level associate to the instability into compressor. Hence, surge is very dependent on the flow pattern produced by the compressor inlet duct and also on the piping upstream and downstream the compressor. Finally, this technique allows to know the behavior of turbocharger compressor for the gas turbines or diesel engines used in electrical power generation.

Key words: Compressor, diesel engine, power generation, surge, turbocompressor, turbocharger.

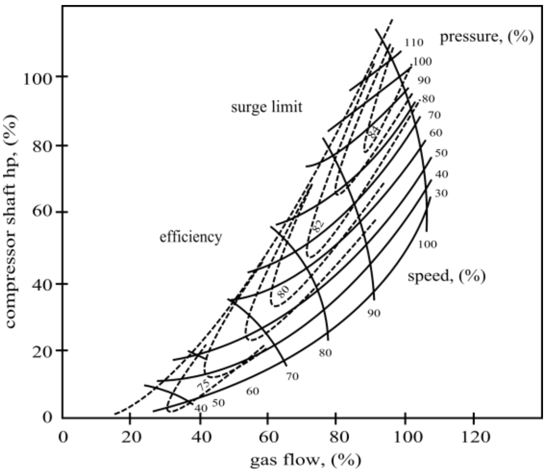

Fig. 1: Typical compressor map where speed lines are a function of horse-power and flow rate [2].

1. Introduction

The turbocharger is a vital part of most modern diesel engines where are widely used in generating electricity in land, marine and transportation. It allows increase of engine power density through the downsizing concept, reducing fuel consumption [9]. An exhaust gas driven turbine (radial-mixed flow for smaller engines and axial for larger ones) powers a compressor that increases pressure of the fresh charge prior to its entry inside the combustion chamber. For example, turbocharged slow speed two stroke diesel engines are among the most efficient thermal power plants, with thermal efficiencies approaching or exceeding 50% [10].

In other hand, gas turbine is used in many applications, and the application determines in most parts the type of gas turbine best suited. The three major types of applications are aircraft propulsion, power generation and mechanical drives.

In the power industry, the gas turbine has traditionally been used in peaking service, especially in U.S. and Europe. In the developing world, the gas turbine has been used as a base loaded plant since the 1960s. Since the 1990s, the gas turbine, being the prime mover in combined cycle power plants, has been developed to operate at high pressures and temperatures, consequently high efficiencies have been achieved [2].

A. Rotating stall

Before of surge phenomenon take place in the compressor another flow behavior. It is normal with compressor that as the mass flow is reduced the pressure rise increases. Generally a point is reached at which the pressure rise is a maximum and further reduction in mass flow leads to an abrupt and definitive change in the flow pattern in the compressor. Beyond this point the compressor enter into either a stall or surge.

Three different ways in which this change in the flow can occur are:

- Progressive stall,
- Abrupt stall, and
- Surge (Fig. 4).

In the first case shown, Fig. 2, the drop in overall performance is quite small, and often the presence of the stall is indicated only by a change in noise or by high-frequency instrumentation inside the machine. This behavior is sometimes called "*progressive stall"*. From this stage, is known that the instability is emerging.

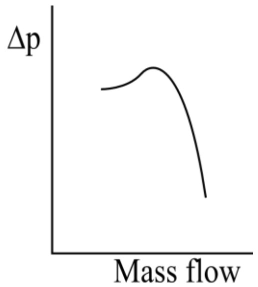

Fig. 2: Progressive stall [4].

The behavior depicted in Fig. 3 leads to a very large drop in pressure rise and flow rate; when the compressor stalls, the mean operating point moves rapidly down along the throttle line to settle at the new point with a pressure rise that might be only a fraction of that before stall for multi-stage compressor. This sometimes referred to as "*abrupt stall"*.

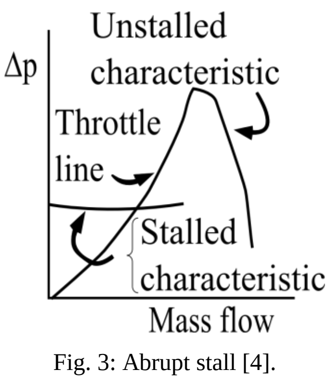

Fig. 3: Abrupt stall [4].

In both case the flow is no longer axisymmetric but has a circumferentially non-uniform pattern rotating around the annulus, giving rise to the term *"rotating stall"*. The annulus then contains regions of stalled flow, usually referred to as *"cells*", and regions of unstalled flow, see Fig. 4. Rotating stall is a mechanism which allows the compressor to adapt to a mass flow which is too small; instead of trying to share the limited flow over the whole annulus the flow is shared unequally, so that some blade passages (or parts of passages) have a quite large flow and some very little. In rotating stall the overall or time-mean mass flow remains constant but the local mass flow varies as the rotating cell passes the point of observation. Inside the stall cells the axial or throughflow velocity is very much less than the unstalled flow but the circumferential component of the velocity can be large. There may be several stall cells or only one and the cells may extend right across the annulus (full-span stall) or only over part (part-span stall). When the cell is full span there normally seems to be only one cell, whereas when the stall is part span there can be multiple cells.

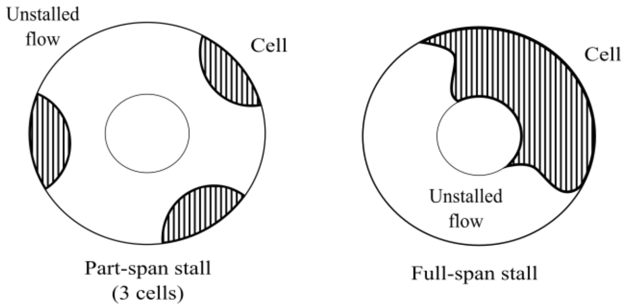

Fig. 4: Different types of rotating stall. Regions of low axial velocity (cells) shown shaded [4].

B. Surge phenomenon

Surge is an instability phenomenon that is known to occur in compressors under low flow conditions [6]. The highly dynamic nature of the phenomenon limits the safe operating region and, hence, the available performance of these machines. At reduced flow rates, the pressure buildup in the compression system reaches a critical point, where the flow characteristics approach a limit cycle. This can be very destructive as reversal of flow could occur in the compressor. Such changes result in sudden thrust load reversal and also high gas temperatures due to the recycling of the compressed gas. These are damaging to both the compressor and its components. There are many uncertainties concerned with surge. These uncertainties of operation include inlet distortion, which may be transient; transient throttle changes, such as occur when a gas turbine is accelerated; transient geometry changes such as tips and axial clearance changes following speed changes; and compressor mechanical damage including blade erosion and the effects of large foreign body ingestion.

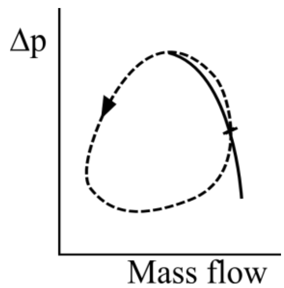

Fig. 5: Surge phenomenon [4].

The type of behaviour depicted in Fig. 5 shows the surge phenomenon [4]. Here the overall annulus averaged mass flow varies with time, so that the entire compressor changes more or less in phase from being unstalled to stalled and again. The process may be so violent that the mass flow is reversed during the left-hand leg and previously compressed gas then emerges out of the inlet; this is sometimes called deep surge. On the other hand it may be very mild so that the operating point orbits around the top of the pressure rise-mass flow characteristic and the main evidence for the surge is an audible burble; such behaviour is quite common with small turbocharger compressor prior to a harder surge when the full reversal of the flow takes place. During some parts of the surge cycle, while the compressor is forced to operate at a low mass flow, the flow may be transiently in rotating stall. The frequency of the surge cycle is set by the times for the storage volume to fill and empty.

A widely adopted industrial practice to protect equipment from surge is to avoid operating the compressor in unstable regions by keeping a safety margin within its operating envelops. The surge margin is usually about 10% of the flow rate away from surge. This *"surge avoidance"* practice limits the useful operating envelop of the compressor and can result in the compressor operating at lower efficiency. A more advanced option involves surge suppression, which relies on accurate system models to develop surge control strategies. Such strategies stabilize the compression system to enable operation in the unstable region.

To cope with these it is normal to specify a quantity known as the *"surge margin"* (even though the compressor may not go into surge but into rotating stall it is conventional to refer to *"surge margin"* and to a *"surge line"* on the compressor operating map).

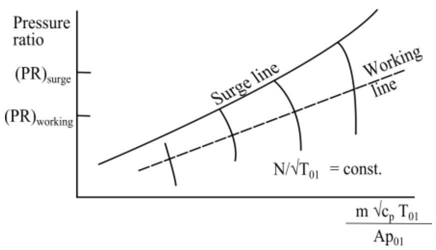

Fig. 6: A compressor pressure ratio-mass flow characteristic used in a method for defining surge margin [4].

There are many different ways of defining surge margin, but one of the most simple is illustrated in Fig. 6, with the surge margin defined by

$$SM = \frac{(PM_S - PR_w)}{PR_w} \qquad (1)$$

where PR_w is the pressure ratio on the working line for a given corrected rotational speed and PR_s is the pressure ratio on the surge line for the same mass flow rate as the condition on the working line [4]. In a multistage compressor for use with turbojet engine it would be normal to insist on a surge margin of about 25%. According to this definition the corrected speed will be higher for the points on the surge line than the working line. If operation is at a single corrected speed it is more appropriate to define a surge margin in terms of the inlet mass flow on the working line and on the surge line for that one corrected speed.

Fig. 7 also shows contours of compressor efficiency on the same axis with more details.

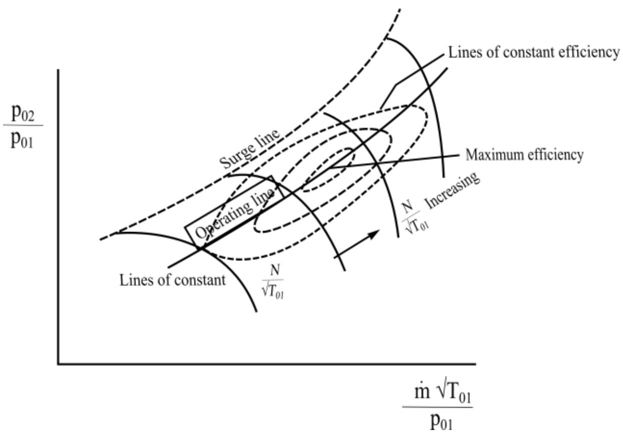

Fig. 7: Overall characteristic of a high speed compressor [6].

Each of the constant speed curves on the compressor characteristic terminate at the surge (or stall) line. Beyond this point the operation is unstable. At high speeds and low pressure ratios the constant speed curves become vertical. In these regions of the characteristic, no further increase in mass flow is possible since the Mach number across a section of the machine has reached unity and the flow is said to be "*choked"*.

In other words, a compressor is able to operate anywhere below and to the right of the surge line. However, it is usually constrained to a single operating line, which is set by the flow area downstream if the compressor. Even so, the operating point at which the flow in the compressor becomes unstable and progresses to surge depends not only on the compressor but on the system in which it is operating: the duct, volume and throttle in a simple test configuration - for a gas turbine the throttle is replaced by the pressure drop in the combustion system and turbine-.

C. Control temperature to characterize the surge

During compressor surge, the compressor performance falls due to the inability of the compressor to handle the increased pressure ratio. The surge may occur due to a variety of reasons, such as, when the inlet airflow temperature becomes distorted during normal operation of the compressor. In addition, surge may occur due to compressor damage or a malfunction of the turbine engine control system [12]. The common technique to detect the surge regimen operation in compressors is using the temperature in the intake manifold. When the surge effect appears in the compressor inlet duct, the temperature become to increase and the instabilities appears in the system. The monitoring of the temperature control allows to know the surge regimen.

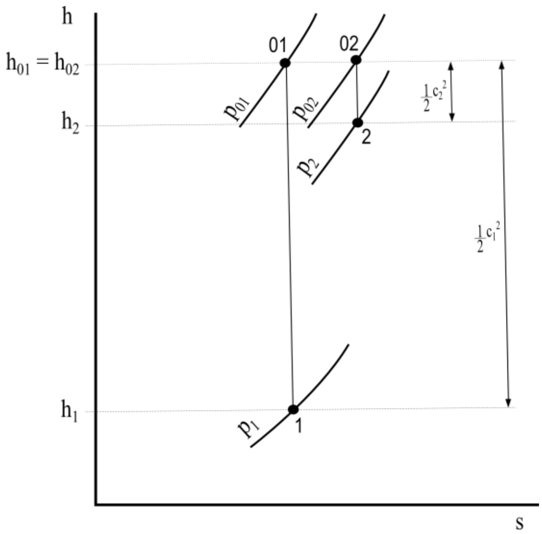

Fig. 8: h-s diagram.

Fig. 8 shows the *h-s* diagram of the system. The stagnation enthalpies are h_{01} and h_{02}. Hence, known the stagnation temperatures T_{01} and T_{02} it is possible to calculate the stagnation enthalpies by means of:

$$dH = C_p \cdot dT \qquad (2)$$

The difference between stages 1 and 2 means the mass flow rate in the machine. At this moment, the fluid is undergoing changes due to emerging instabilities. Fig. 8 indicates that the stagnation enthalpies -total energy level- is constant but the interest area is focused on static variables and kinetic energy terms. Thus, it is possible to know about energetic condition of the fluid.

Nevertheless, the method to measure the static temperature is complex and requires instrumentation development.

2. Diesel generator and turbomachinery in energy generation

Diesel generators, sometimes as small as 200 kW are widely used not only for emergency power, but also many have a secondary function of feeding power to utility grids either during peak periods, or periods when there is a shortage of large power generators. Sizing of diesel generators is critical to avoid low-load or shortage of power and is complicated by modern electronics, specifically non-linear loads. Set sizes range from 8 to 30 kW for homes, small shops and offices with the larger industrial generators from 8 kW up to 2000 kW used for factories. Furthermore, ships often also employ diesel generators, sometimes not only to provide auxiliary power for lights, fans, winches and more, but also indirectly for main propulsion [5].

In size ranges around 50 MW and above, an open cycle gas turbine is more efficient at full load than an array of diesel engines, and far more compact, with comparable capital costs; but for regular part-loading, even at these power levels, diesel arrays are sometimes preferred to open cycle gas turbines, due to their superior efficiencies.

In power generation, the gas turbines can be further divided into three categories [2]:

1. Small standby power turbines less than 2 MW. The smaller sized of these turbines in many cases have centrifugal compressors driven by radial inflow turbines, the larger units in this range are usually axial-flow compressors sometimes combined with centrifugal compressor at the last stage, and are operated by axial turbine.
2. Medium-sized gas turbines between 5-50 MW are a combination of aero-derivative and frame type turbines. These gas turbines have axial-flow compressors and axial-flow turbines.
3. Large power turbines over 50-480 MW, these are frame types turbines. The new large turbines are operating at very high firing temperatures of about 1315 ºC with cooling provided by steam, at pressure ratios approaching 35:1.

3. Conclusion

A common technique to detect the surge phenomenon has been by means of monitoring the temperature in the compressor inlet duct [1]. In the intake manifold, when the instabilities become intense, the temperature increases proportionally [8]. This explains because the temperature gradients begin to appear before the surge phenomenon occurs and its magnitude depends to the compressor size, among others. Additionally, the temperature gradients have an important correlation with the noise level associate to the instability into compressor. Hence, surge is very dependent on the flow pattern produced by the compressor inlet duct and also on the piping upstream and downstream the compressor [7].

However, this method use the stagnation temperature that provides information when the surge phenomenon appears, but not when conditions of the surge phenomenon is emerging.

By this way, it is possible to know about energetic condition of the fluid when use a combination of static temperature and stagnation temperature.

This work improves a possible method to measure the temperature and study the difference between the piping upstream and downstream from compressor. This way, it is plausible to obtain the energetic level of the fluid.

Finally, this technique allows to known the behaviour of turbocharger compressor for the gas turbines or diesel engines used in electrical power generation. Thus, will be possible to determine the instabilities due to the surge phenomenon that affect the engine or turbomachinery operation, being a problem in the power industry.

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