VARIABLE PITCH FANS EVOLUTION PROOFING UNDERGROUND WORKS

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ABSTRACT

The Fréjus road tunnel which connects France and Italy under the Alps between Modane (FR) and Bardonecchia (IT) is currently undergoing a major renovation of its ventilation system.

The 24 machines providing sanitary ventilation and smoke extraction for the tunnel will be replaced by machines not normally used in the world of road tunnels: fans with a blade angle that can be adjusted during operation, with a 2120 mm diameter, a motor of 1 MW power and high temperature resistance (400 °C/ 2 hours) without external cooling

Used with variable speed drives, these variable blade angle fans are able to offer optimized operating points for all possible configurations. They are therefore capable of maintaining the expected performance, despite changes in atmospheric conditions (pressure, temperature) or changes that may occur in the air flow system over the long term.

The blades are controlled by means of a hydraulic unit that moves cylinders to vary the blade pitch angle and therefore the air flow and pressure developed by the fan.

The development and construction of these machines required a lengthy design process and was finalized with high temperature operating test at 400 °C during 2 hours. During this destructive test, the test unit was inserted into a hot air circuit to validate its operation according to EN 12101-3. The first site tests carried out in the plant on the French side of the Fréjus tunnel validated the sizing of the fans. The use of engine drive speed variation technology together with the adjustable pitch angle also makes it possible to achieve the highest ventilation efficiency of the fan, regardless of the configuration of the network.

This also directly translates into a reduction in the motor's power consumption, an important optimization for sustainable development.

Keywords: road tunnel, variable pitch fan, performance, temperature test

1. INTRODUCTION

The Fréjus road tunnel is a cross-border tunnel that is almost 13 km long, connecting Modane and Bardonnechia. It is currently one of the main road crossing points in the Northern Alps.

It consists of a single bidirectional tube accommodating two 3.55 m lanes. It has been designed to accommodate heavy goods vehicles up to a maximum height of 4.30 m.

A transverse ventilation system was chosen during the tunnel’s design. In normal operating conditions, this system consists mainly of injecting fresh air and/or extracting stale air at regular intervals to dilute pollutants. In the event of a fire in the structure, this system’s strategy consists of working to obtain a natural smoke stratification and to extract the smoke from the ceiling. This classic system is usually combined with jet fans located in the tube in order to effectively control air flow - this provision is planned as part of the ventilation system renovation.

In the case of the Fréjus tunnel, the two ducts are positioned above the traffic flow space. One allows the extraction and evacuation of stale air or smoke via approximatively 100 hatches located every 130 m in the tunnel ceiling. The other is used to inject fresh air into the tunnel using 2,860 air outlets located every 4.5 m.

With a total capacity of 1,500 m³/s for the supply of fresh air and 1 250 m³ / s for the evacuation of stale air, the ventilation system is also composed of 24 fans (12 for fresh air, 12 for stale air), distributed across 6 ventilation plants:

- Ventilation plant A, at the head of the tunnel, French side,
- Ventilation plant D, at the head of the tunnel, Italy side,
- The 2 ventilation plants B (at 1st third),
- The 2 ventilation plants C (at 2nd third).

The ventilation plants A and D are supplied with fresh air through the tunnel heads, while the ventilation plants B and C are supplied by vertical ventilation shaft approximately 700 m in height, one on the French side and the other on the Italian side. These vertical ventilation shaft, with double ducts, are also used for the evacuation of stale air (Figure 1). To cope with the pressure variations in the structure, due for example to variations in climatic, operating and traffic conditions, it was necessary to consider fans that are capable of adapting their operating air flow / pressure point operation.

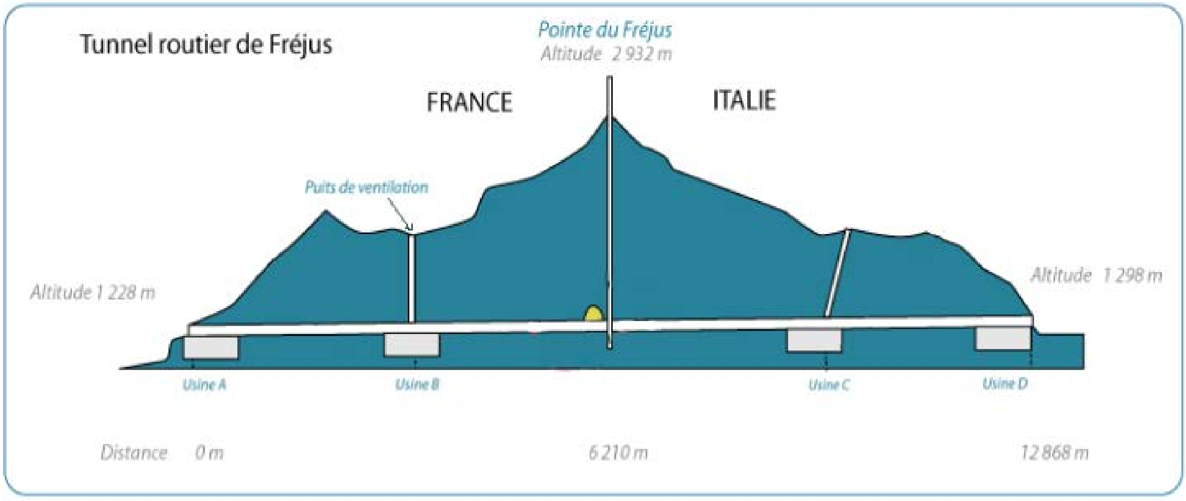

Figure 1: Profile of the Fréjus road tunnel

This is why the Fréjus tunnel was equipped with fans that can vary their blade pitch while in operation. This equipment is unusual in the world of road tunnels, but it is able to offer optimized operating points for all of the envisaged configurations, maintaining the required performance levels, despite the pressure changes in the ventilation networks.

2. THE INFLUENCE OF GEOMETRY ON PERFORMANCE

To reach the desired air flow rate in the structure, the air that is expelled or sucked in by the fans must compensate for the pressure losses in the circuit, i.e. any friction or other obstacles which accompany (and inevitably oppose) the flow of air in the circuit.

In order to determine the pressure rise required to develop the desired air flow, pressure loss calculations for the fan’s aeraulic circuit need to be carried out. These flows involve regular and singular pressure losses, according to the following breakdown.

Regular pressure losses

The pressure loss in a pipe depends on the dimensions of the pipe. The longer it is, the more friction there will be along its walls. The narrower it is, the greater the friction along the walls over the entire flow. The dimensions of the pipe as well as the roughness of the walls of this pipe therefore have a strong influence on the pressure loss.

The ventilation system of the Fréjus tunnel is divided into 3 sections:

- Section1, located between metric point 0 and 4,170, supplied by:
    - Section 1: 4 fans: 2 fresh air fans (AF) and 2 exhaust air fans (AV) from the ventilation plant on the French tunnel head side,
    - Section 2: 4 of the 8 fans in plant B;
- Section 2, located between metric point 4,170 and 8,838, supplied by:
    - Section 3: the remaining 4 of the 8 fans in ventilation plant B,
    - Section 4: 4 of the 8 fans in plant C;
- Section 3, located between metric point 8,838 and 12,897, supplied by:
    - Section 5: the remaining 4 of the 8 fans in ventilation plant C,
    - Section 6: the 4 fans from ventilation plant D on the Italian tunnel head side.

The Fréjus tunnel's ventilation system:

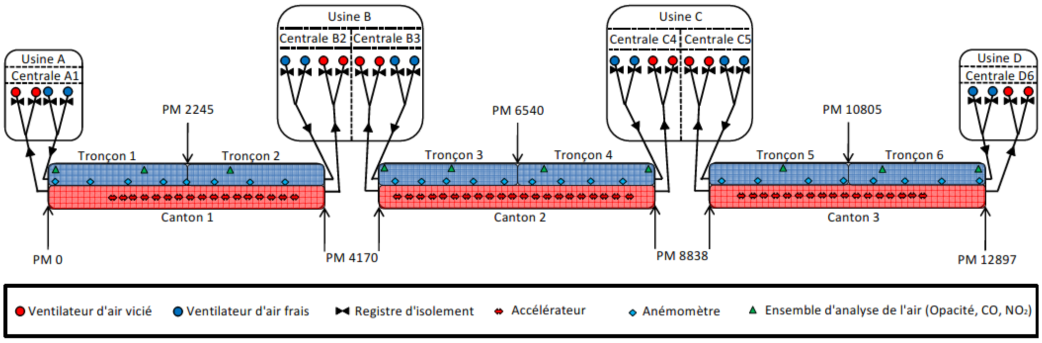

Figure 2: The Fréjus road tunnel's ventilation system

Therefore, each ventilation plant supplies the tunnel with fresh air via a fresh air duct with a length of just over 2000 m and a cross-section of around 10 m², generating a significant linear pressure loss. To supply sections 2 and 3, air arrives at plant B through a vertical shaft that is 700 m high with a cross-section of approximately 20 m². Likewise, for sections 4 and 5, air arrives at plant C via a 690 m long oblique shaft with a cross-section of about 12 m². These 2 shafts also generate linear pressure losses in the circuit.
By way of illustration, the energy loss in the ducts, for an air speed of 22 m/s, is 1,000-1,200 Pa in the fresh air duct and 650-750 Pa in each shaft.

Singular pressure losses

The pressure loss in a duct also takes into account the resistance to air flow caused by accidents such as section changes (widening, narrowing), direction changes (elbows, curves), connections (separation or joining) and all obstacles such as grids, registers, processing parts, etc.

The transition from ventilation plants to ventilation ducts results in numerous bends as well as cross-section widening and narrowing. In addition, the distribution of fresh air in the tunnel wall is undertaken by ducts with a small cross-section distributed every 4.5 m, which follow the wall of the structure, connecting to the traffic tube via vents in the lower part of the tunnel.

The total pressure loss in the aeraulic network of the Fréjus tunnel is the sum of the regular pressure losses due to the friction of the air against the walls of the circuit and the singular pressure losses due to the separation of the air streams when these pass specific singular points or obstacles, to which are added the pressure differences between the tunnel and the exterior.

The pressure loss calculation include a margin of error. Indeed, we will see that a lot of elements can generate variations in the pressure calculation.

3. THE ORIGINS OF PRESSURE VARIATIONS

Unexpected obstacles

The air flow network in an underground structure is linked to the geometry of the structure itself and to the equipment installed, and during a project, this network is modified many times. This creates a synchronization problem for the entity in charge of dimensioning the ventilation equipment. At the start of a design study for a structure, ventilation power must be provided quickly in order to size electrical equipment. The pressure loss calculations are therefore carried out using initial plans to quickly freeze power requirements as input data for other trades. During the life of the project, these plans evolve and aeraulic obstacles appear. These unforeseen obstacles have the consequence of making the air path more difficult and thus increasing the energy required by the fan to be able to circulate the desired flow.

Variations in climatic pressure

In addition to the pressure losses linked to the geometry of the structure and the aeraulic network, there will be additional pressure variations linked to the location of the structure (location, altitude) and its frequentation (traffic level, proportion of heavy goods vehicles).

Due to both climatic position (a high temperature amplitude can be encountered) and strategic position (it is a very busy transalpine road axis), the Fréjus tunnel is subject to variations in pressure which can change over time.

At its two heads, an underground structure is subjected to variations in atmospheric pressure due to local climatic variations. Thus, the conditions of the pressure calculation can vary according to the seasons and modify the flow rates necessary to obtain ventilation objectives.

In addition, the air circuit itself is subject to temperature variations. The temperature inside the tunnel is around 30 °C and the temperature outside the tunnel can fluctuate around -10 °C or even -20 °C in winter at the shaft bay levels.

The pressure loss calculation involves the air density, this depends on several factors:

- Temperature;
- Atmospheric pressure;
- Relative humidity.

Thus, at 20 °C and 1013 hPa the density will be 1.2 kg/m³, however at 0 °C it will be 1.28 kg.m³, an increase of 6.7%. This increase has a direct influence on the ventilation power of the fan, which will increase by the same ratio.

This difference in temperature between the interior and the exterior of the tunnel is particularly manifested in the shafts. Indeed, in addition to the pressure losses created by the linearity and the changes in the shafts, it is necessary to add the additional pressure loss due to the temperature difference between the 2 ends.

This difference in pressure on either side of the shaft is expressed as a first approximation as follows [SIA 96]:

$$\Delta p = \Delta H \times 9{,}81 \, (\rho_a - \rho_S)$$

With:

- ΔH : height of the shaft
- ρ_a : density of outside air, average over ΔH,
- ρ_s : density of the air in the shaft, average over ΔH.

For the 700 m high shaft on the French side, this pressure difference can be 750 Pa if it is 0 °C at the top of the shaft and 1050 Pa if it is -10 °C.

The fan must therefore supply a variable pressure to counter the seasonal pressure variation, as well as those that occur between daytime and night time.

The piston effect caused by vehicle traffic

The presence of vehicles in the tunnel has an impact on the ventilation of the structure. Not only can the presence of vehicles, especially heavy goods vehicles, block the tunnel and prevent the air flow, but vehicles also generate additional resistance through the piston effect when they move in the tunnel.

Depending on the direction of traffic flow in relation to the ventilation direction, the mass of air displaced by vehicles increases or decreases the speed of the air in the tunnel.

In the Fréjus tunnel, 2 front heavy good vehicles with cross-sectional area of around 10 m^2, will occupy a little more than half the tunnel cross-section. The blocking effect is therefore very important.

In terms of the piston effect, vehicle traffic is bidirectional. It can therefore occur alternately in one direction then in the other depending on traffic conditions.

To comply with these pressure variations, the Fréjus tunnel has been equipped with fans capable of adapting their operating point.

4. VARIABLE PITCH FANS IN OPERATION

The working principle

One of the most important parameters in the design of any turbo machine is the angle which the outer edges of the blades make with the tangent of peripheral motion. As this angle is increased, the volume flowrate will also increase, and this applies to axial, mixed flow or centrifugal fans. At the same time the pressure, which is a function of the swirl, remains substantially constant.

If the pitch of an axial flow fan’s blades could be altered in motion, then an effective flow rate control method would be available. The technology to do this already existed in aircraft propellers, albeit with a considerably lower number of duty hours than what is necessary for a ventilation fan. Nevertheless, over the last few years, the necessary systems have been simplified enabling a sufficiently reliable fan to become available for normal ventilation applications.

Variable pitch axial fans can be used with constant resistance, constant volume flow, or constant pressure systems-in fact with any form of system characteristic. The overall energy savings are among the highest available across all types of flow rate control. A unique feature is the ability to control volume flow down to zero even at constant pressure. Standard continuous hydraulic or electric control systems can be employed, and the response speeds can be tailored to requirements. Noise level falls with reduction of volume flow, whereas it tends to rise with damper or vane control; the fall is not nearly so rapid as it is with speed control, but the use of a variable speed fan-motor with a variable pitch impeller can satisfy all of these conditions.

The manufacturing principles

Centrifugal forces are predominant in the mechanical design. The centrifugal force on an individual fan blade can be considerable and is a function of the blade weight and its rotational speed. The centrifugal force on a mass of m (kg) revolving at w (rad/s) at a radius of R (m) is:

$$F_c = mw^2R$$

For the 2120 mm axial fan at 1491 rpm, the angular velocity is w = 156.1 radians/s. Taking m, the mass of one blade, as 24.1 kg, and its radius of gyration, R, as 1.06 m, the centrifugal force per blade will be:

$$F_c = 622.4\ kN$$

This is nearly 2600 times the weight of the blade, which is 24.1 x 9.8 = 236.2 N and the situation is sometimes spoken of as equivalent to operating in a gravitational field of 2600 g where g = 9.8 m2/s is the acceleration due to gravity at the earth's surface.

Such a force, and indeed forces several times as great, are within the static capacity of ordinary ball-thrust bearings and these are commonly used to carry the centrifugal force at the blade root while permitting blade rotation with minimum friction.

Levers at the base of each blade translate the common pitch angle adjustment into axial movement of a sliding member within the hub. This may be actuated in four ways:

- Automatically, through the expansion of a pneumatic reinforced rubber bellows against a spring within the hub. The bellows is fed with compressed air through a rotary air seal on the shaft extension.
- Automatically, through a lever system where an external hydraulic or electric cylinder applies pressure to the stationary race of a ball thrust, bearing the revolving race of which is coupled to the sliding actuator within the hub.
- Automatically, through an external hydraulic or electric cylinder which applies actuating force while the reaction force is transmitted from the hub to the body of the cylinder through a second thrust bearing. This arrangement relieves the main fan bearing of control thrust load.
- Manually, by means of a screw jack when the fan is at rest.

The figure below shows the cross-section of the hub of a variable pitch axial fan with inbuilt hydraulic control. The oil pressure can be adjusted by the control system to any value between 0 and 100 bar. For each value there is a corresponding compression, position of the sliding actuator, and pitch angle of each blade. When the fan is running forces must be applied to each fan blade to keep them at the required pitch angle. Without any intervention, they would rotate to a position near zero pitch angle where the centrifugal forces on each blade are in balance. Weights are attached to the blade root in such a position that they apply a counterbalancing turning moment and minimize the required actuating force.

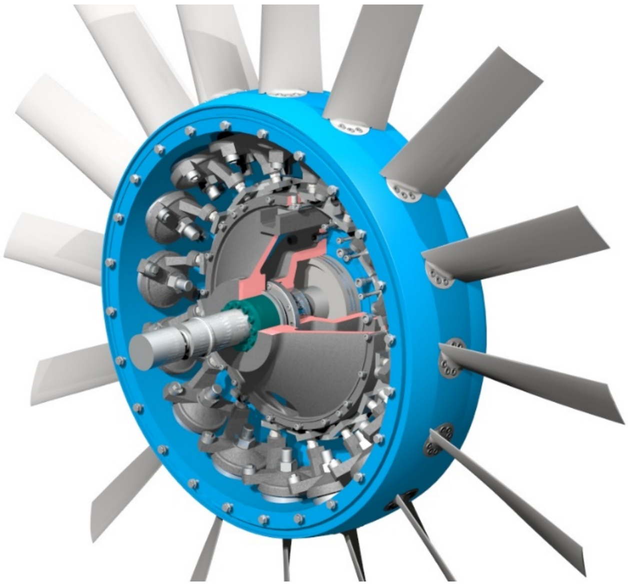

Figure 3: Variable pitch axial fan impeller with hydraulic blade adjustment

5. PERFORMANCE OF A TYPICAL VARIABLE PITCH FAN

The aerodynamic design of a variable pitch axial fan can be exactly the same as that of a general purpose adjustable pitch fan

The figure below shows the working curve of an existing axial exhaust fan with variable pitch angle located in the Fréjus tunnel. The fan’s total pressure and inlet volume flow are plotted for a pitch angle range from 5° to 55°. Contours of constant fan total efficiency are also plotted from the peak of about 87.5% down to 40%.

Plotted working points, from 1 to 8, are examples of the range of system characteristics which can be dealt with by this fan.

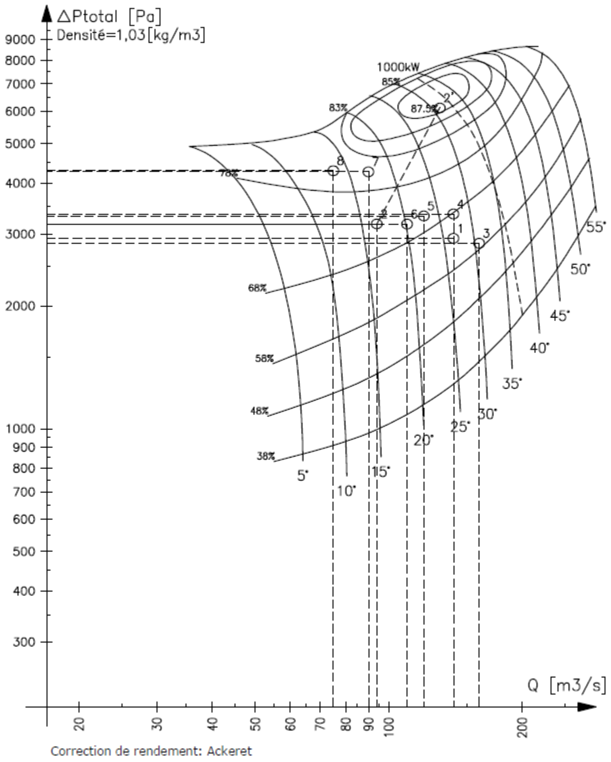

Figure 4: Working curve for variable pitch angle exhaust fan installed in the Fréjus tunnel

System characteristics differ from working point 3 (low circuit resistance corresponding to an extraction point near to the fan) to working point 8 (high circuit resistance corresponding to an extraction point at 4 km from the fan). Using a fixed blade angle fan for these two cases, adjusted to 31° to achieve working point 3, would be not possible as the fan would be very close to stall in working point 8 conditions.

One of the main advantages of fan installation in the Fréjus tunnel is the possibility of achieving highest peak efficiency for the fan for all working points. The table below shows point 2 adjustment when the motor is rotating at its nominal speed once the blade angle is set to 16°:

Table 1: Working point 2 characteristics for a Fréjus tunnel exhaust fan at nominal speed

Flow (m^3/s)	94
Total pressure (Pa)	3176
Efficiency (%)	72
Blade angle (°)	16
Shaft power (kW) at density 1.03kg/m^3	414.6

Using frequency converters, point 2 could be obtained optimizing the aerodynamic efficiency of the fan aiming for the highest efficiency at the circuit resistance for this point. As shown in figure 2, the highest efficiency point at the same circuit resistance would be point 2'. The table below shows point 2 adjustment when the motor is rotating at reduced speed once the blade angle is set at its highest aerodynamic efficiency:

Table 2: Working point 2' characteristics on a Fréjus tunnel exhaust fan at reduced speed with optimal blade angle

Flow (m^3/s)	94
Total pressure (Pa)	3176

Efficiency (%)	87.5
Blade angle (°)	31
Shaft power (kW) at density 1.03kg/m^3	341.2

Every working point can be easily obtained by modifying the blade angle using the continuous and stable hydraulic adjustment to adjust it to its highest efficiency and by setting the corresponding rotation speed. Comparing table 1 and 2, power benefits are clearly demonstrated once the optimal blade angle is obtained for each working point condition. Energy saving at this working point is 17.7%, from 414.6kW to 341.2kW.

6. APPLICATIONS OF VARIABLE PITCH FANS

The versatility of the variable pitch axial fan is evident from the above example. It was seen that over 78% efficiency is maintained over a power input range of 100% to 25% in each variable volume case; efficiency is still 50% at less than 10% of full power. It is not necessary for the whole load to be managed by one fan. Large volumes or pressures can be dealt with by using one or more variable pitch fans in parallel with a similar number of fixed pitch units.

The followings are all examples of successful applications of variable pitch axial:

- Long vehicle tunnels where working conditions can be affected by fire location or degraded mode;
- Main mines ventilation adjusted depending on mine layout;
- Power stations;
- Laboratories and wind tunnels.

7. CONCLUSION

The dimensioning of ventilation in underground structures involves pressure loss calculations in complex and variable networks. In addition, the climatic conditions linked to the location of the structures influence the performance requirements of the ventilation system. The fans installed are very powerful machines, but conversely they are also very sensitive to variations in their working conditions. This sensitivity will affect the flow rates achieved and also their yield and therefore their energy consumption. When these constraints are pushed to their limit, as is the case of the Fréjus tunnel, the use of machines that can vary the pitch angle of their blades is fully justified. This system then makes it possible to achieve the desired objectives with great flexibility and energy consumption optimization. The initial investment costs are then offset by the adaptability of the system to modifications that may occur during the life of a complex structure and by the daily savings on energy consumption.

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Finally, our thoughts also turn to Jean Philippe COLLET and his relatives, who was particularly involved in the implementation of ventilation systems and who represented in a way the soul of the Fréjus ventilation system, and from who we modestly wish to take up the torch.