Inlet Influence on the Pressure and Temperature Distortion Entering the Compressor of an Air Vehicle

P. Hendrick
Université Libre de Bruxelles, ULB
Avenue F.D. Roosevelt, 50
1050 Brussels
BELGIUM

patrick.hendrick@ulb.ac.be

ABSTRACT

One of the possible origins of High Cycle Fatigue in a compressor blade is the rotating stall under the influence of (rotating) inlet pressure or temperature distortion leading to a varying angle of attack on the compressor blades.

This paper will be oriented towards the propagation of total pressure and total temperature non-uniformities in axial flow fans and compressors and their subsequent effect on downstream and upstream stages. An analytical technique will be used to correlate the inlet distortion patterns to the reduction of the stall/surge margin.

A first part of this paper is dealing with the role of the inlet on the total pressure and temperature distortion at the fan or compressor face. A second part is concentrated on distortion propagation through the compressor. Given a total pressure or total temperature distortion entering a compressor, the methodology developed in this paper allows to predict the downstream total pressure and pressure ratio and therefore to give insight into the potential danger of a given inlet distortion pattern.

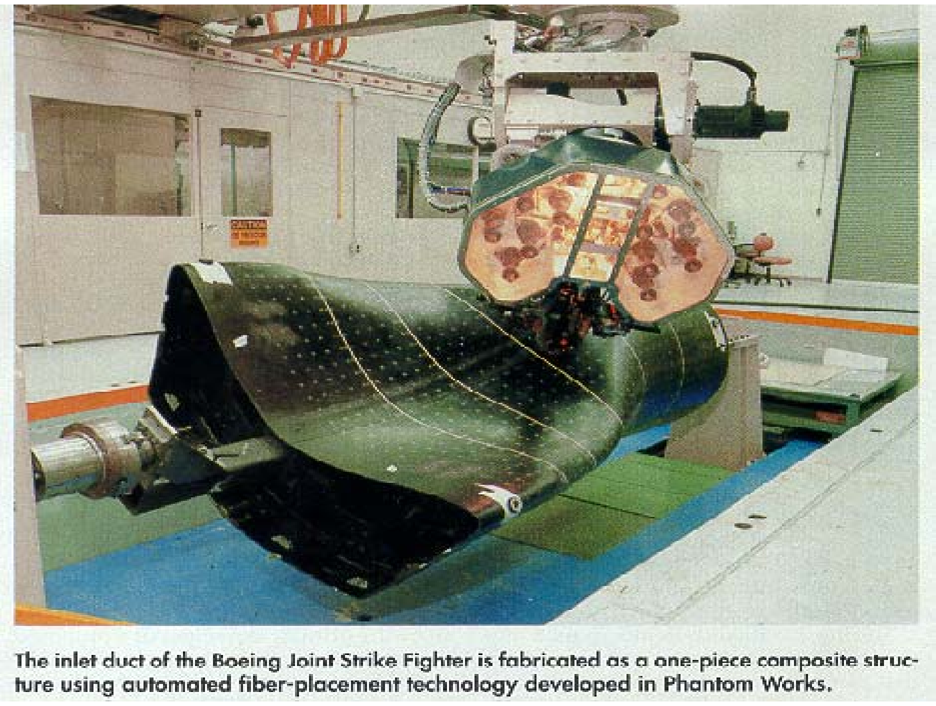
1.0 INTRODUCTION

An important contributor to the HCF-problems in compressor blades is the response to aerodynamics forcing generated by upstream stators, Inlet Guide Vanes (IGV's) and distorted inlet flow conditions. This is particularly bad in non-typical axial-flow compressors like in new applications as a lift-fan duct with a high turning angle before entering the fan, an effect becoming even worse with increasing flight speed. Under such adverse operating conditions, IGV's are probably not able to clean up the high inlet distorted field and could even induce higher responses in the downstream blades.

Pressure distortion due to the inlet can be of very different origins, ranging from reasons due to a high angle of attack, side wind, position of the inlet compared with the main rotor and the turboshaft exhaust in a helicopter or shock-boundary layer interaction in a supersonic external compression inlet as on the MIG-29 (Fig. 1). It is even quite possible that the inlet itself introduces a pressure swirl distortion due to its geometry or its change of geometry as in the case of the JSF intake (Fig. 2). This concern can thus become of particular importance for such a special inlet as in the case of STOL and lift-fan.

Hendrick, P. (2005) Inlet Influence on the Pressure and Temperature Distortion Entering the Compressor of an Air Vehicle. In *Evaluation, Control and Prevention of High Cycle Fatigue in Gas Turbine Engines for Land, Sea and Air Vehicles* (pp. 8-1 – 8-8). Meeting Proceedings RTO-MP-AVT-121, Paper 8. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Figure 1: Supersonic Inlet on the MIG-29 (one open & one closed).



The inlet duct of the Boeing Joint Strike Fighter is fabricated as a one-piece composite structure using automated fiber-placement technology developed in Phantom Works.

Figure 2: Intake of the Boeing JSF Prototype.

2.0 INLET INDUCED DISTORTION PROPAGATION

The inlet cannot correct the distortion through the diffuser length. Very often, the pressure distortion, for example, is still present at the compressor face and then enters the fan or the compressor. An example is given on Table 1 for the pressure distortion measured at the compressor face of a helicopter turboshaft on a test bench equipped with a “clean” mock-up of the helicopter intake or with a particle separator (“sand” filter) mounted on this intake ([1]).

Table 1: Example of Pressure Distortion Induced by an Inlet

	Pressure distortion (%)		
Mass Flow (kg/s)	Distortion limit (%)	Standard A109 Intake	With an inlet particle separator
1,71	± 5,0	5,72	5,57
1,46	± 4,5	3,92	4,18
	Circumferential pressure distortion DC 60 (%)		
1,71	± 1,0	0,99	0,24
1,46	± 0,9	1,22	0,29

Under the influence of such an inlet distortion, a rotating stall can be induced in an upstream stage of the compressor and this may create a rotating instability on the downstream stage and on its turn affect its stability, reducing the stability margin (SM) of the compressor (Fig. 3).

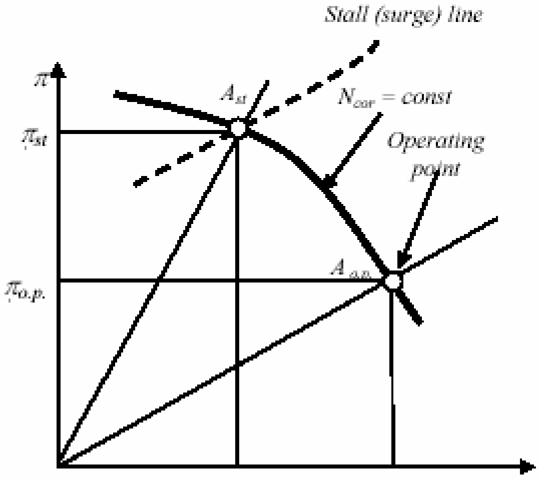


Figure 3: Compressor Performance Map with the Surge Margin Indicated.

Such a problem of rotating inlet distortion on multistage compressor has been studied several times experimentally ([2]) and numerically ([3]).

3.0 A CONTROL THEORY APPROACH

All known publications on this topic are without real theoretical explanations of the experimental results but one can try to give one based on a non-linear and non-stationary model of a compressor absorbing a rotating inlet distortion. In this model, the non-linear and non-stationary characteristics of the compressor is then linearized using the method of harmonic linearization for multi-frequency oscillations ([4]).

Some authors represent these effects of rotating inlet distortion on multistage compressor stability on a map of the flow coefficient ϕ vs. the fraction of distortion speed compared to the rotor speed. That leads to the so-called "dromedary" shape (Fig. 4.a) or "bactrian" shape (Fig. 4.b) (Case 1: uniform inlet ; case 2: stationary inlet distortion ; case 3: minimum flow range with rotating distortion).

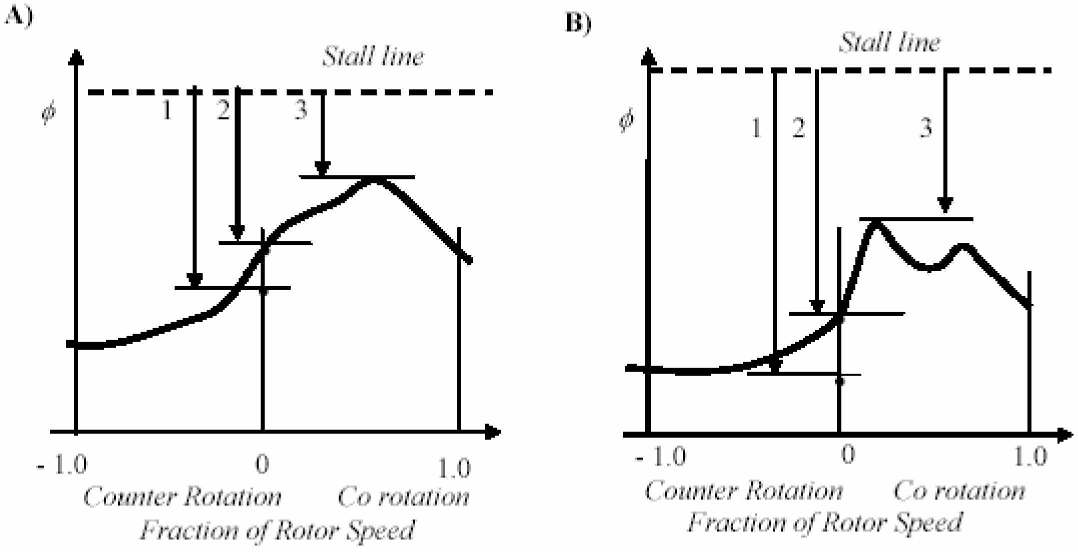


Figure 4: Evolution of SM against Distortion Rotation Rate.

When considering a compressor as a dynamic system with a certain gain factor G (to be extracted form its performance map), one can study the stability of this compressor, which is in fact the evolution of its SM by studying the evolution of its gain factor G. When G decreases, the SM will also decrease. For a compressor, this gain factor G at the operating point (o.p.) is defined as:

$$G_{o.p} = \left[\frac{\partial \pi_{o.p}}{\partial \dot{m}_{o.p}}\right]_{N_{cor}=const;\, \dot{m}_{o.p}=const}.$$

The variation of G in function of the distortion rotation rate is in fact a direct representation of SM. As, in a dynamic system, calculating the gain factor variation in function of the (inlet) distortion rotation rate can become a very complicated problem, one will assume a few assumptions:

- one does not consider the rotor rotation but only two frequencies: the one of the inlet pressure (or temperature) distortion (ω_d) and the one of the compressor pressure oscillations (ω_{st});
- the distortions are not sinusoidal but one can replace the influence of periodical disturbances on SM by the influence of sinusoidal disturbances on G;
- only the compressor is considered in the analysis, not the system with throttling valve.

The compressor can then be described by the five following equations (p represents the stagnation pressure) where Δm_d and Δm_{st} represent the fluctuations of the air mass flow rate at the distortion frequency and at the rotating stall frequency:

$$p = p_{in,0} + \delta p_d \sin(\omega_d t + \alpha).$$

$$P_{out} = p_{in} \cdot \pi$$

$$\pi = \pi_0 + K_1 \dot{m} + K_2 \dot{m}^2 + K_3 \dot{m}^3$$

$$\dot{m} = \dot{m}_0 + \Delta\dot{m}_{st} \sin \omega_{st} t + \Delta\dot{m}_d \sin(\omega_d t + \gamma),$$

$$\begin{aligned} p_{out} &= \left[p_{in,0} + \delta p_d \sin(\omega_d t + \alpha)\right] \times \\ &\times \left[\pi_0 + K_1 \dot{m} + K_2 \dot{m}^2 + K_3 \dot{m}^3\right]. \end{aligned}$$

The non-stationary exit pressure P_{out} from the compressor can then be expressed as a Fourier series based on the stall frequency ω_{st} and its harmonics. The gain factor G of the compressor must then be expressed separately for each frequency (ω_{st}, $2\omega_{st}$, $3\omega_{st}$ ...) as SM depends on this frequency.

For example, for the first harmonic ω_{st}, the gain of the compressor only is a non-linear non-stationary function of the shape:

$$G(\omega_{st}) = \frac{\partial p_{out}}{\partial \dot{m}}(\omega_{st}) = \frac{b_1 + i a_1}{\Delta \dot{m}_{st}} = G_{b1} + i G_{a1}$$

This G-factor for the 1st harmonic contains two groups of components: one with cosine functions (G_{a1}) and one with sinusoidal functions (G_{b1}). Each one of these two groups (the cosine and sine parts of P_{out} in fact) can be written as follows (where J_i represents the frequency link between ω_d and ω_{st} with a minus signed in case of counter-rotation):

$$G_{b1} = G_{0,b1} + \sum_{i=1}^{9} G_{i,b1} J_i$$

The functions $G_{i,a1}$ and $G_{i,b1}$ are not trivial as they are functions of a lot of parameters. They still need to be established.

When these functions are known, the pressure ration π_c on the surge line may be calculated in function of the inlet distortion frequency. One "just" need to calculate the upper envelope of the individual characteristics for several frequencies. That could help in understanding the number of peaks appearing in an experimental result as shown in Figure 4.

4.0 A FEW PRELIMINARY RESULTS

One can show that, with this control theory where the compressor is considered as a dynamic system, its stability margin (or surge margin) will be varying with:

- the compressor non-linear characteristics, its rotation speed and throttling valve (parameters π_o, K_1, K_2 & K_3)
- the air condition at the inlet ($P_{in,o}$)
- the distortion amplitude (δp_d)
- the amplitudes of the oscillations of the mass flow rate (Δm_d and Δm_{st})
- the phase angles of the oscillating parameters (α and γ)
- the ratio of the inlet distortion and compressor pressure oscillation frequencies (ω_d / ω_{st}).

The curve of the pressure ratio increase at surge vs. distortion frequency can be obtained as the upper envelope of the characteristics for several frequency ratios. These peaks are possible in the following ratios ω_d / ω_{st}: 1, 2, ½, 3, 1/3, 4, ¼, 3/2, 2/3 (multiplied by +/- 1 in function of the rotation direction of the distortion). But all these peaks will not appear. Some of these frequency ratios leading to peaks in the curve which are close to each other and cannot be separated.

From this theory, the gain factor and thus the SM will also change with direction of rotation of the distortion (co-rotating or counter-rotating). This is also observed in the experiments.

5.0 CONCLUSION

A first approach for the estimation of the surge margin in case of inlet pressure or temperature distortion has be given based on the control theory of non-linear non-stationary systems.

The surge margin will be depending largely on the ratio between the distortion frequency and the compressor outlet pressure oscillation frequency.

The number of peaks in Figure 4 which are obtained experimentally can be explained. We can have one, two, three or even more.

The surge margin can be positively or negatively influenced by a counter-rotating inlet distortion.

REFERENCES

[1] P. Hendrick, User experience with the Allison 250-C20R/1 turboshaft on the Belgian Army Agusta A109, RTO AVT Fall Symposium, Ottawa, Oct 1999.

[2] T. Peters & L. Fottner, Effects of co- and counter-rotating inlet distortions on a 5-stage HP compressor, GT-2002-30395, Amsterdam, 2002.

[3] M. Davis et al., An argument for enhancement of the current inlet distortion ground test practice for aircraft gas turbine engines, ASME J. of Turbomachinery, Vol. 124, pp. 235-241, 2002.

[4] J. Pismenny, Harmonic linearization of single-valued non-linear characteristics in the case of two-frequency oscillations, Engineering Cybernetics, Vol. 16, No. 1, pp. 135-143, 1978.

SYMPOSIA DISCUSSION – PAPER NO: 8

Author's name: P. Hendrick

Discussor's name:

Question: Have you tried your method for T_t distortion?

Answer: Not yet, but it is our purpose to do so. We have experimental data on a helicopter turbo-shaft . It would be necessary to try the method on a case with combined P_t and T_t distortions.