Study for the Effect of Combined Pressure and Temperature Distortion on a Turbojet Engine

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Abstract

This paper describes how the effect of inlet flow distortion to a turbojet can be evaluated by a distortion model of whole engine, which is based on mass, momentum and energy conservation, and has been proved to be a valid tool for evaluating the effects of inlet flow distortion on turbofan.

In this model, pressure (or temperature) distortion is quantified with coefficient which associates the pressure (or temperature) in the spoiled sector with the value in the clean sector. Detailed computation and analysis under different overlap phase and distortion intensity are conducted on the stability of turbojet after the representation of combined distortion index. It can be concluded that there is a maximal loss of stall margin when total pressure distortion sector laps over total temperature distortion sector completely. The reduction of stall margin arising due to combined inlet distortions can be minimized through the optimization of a disturbance overlap phase.

Keywords: Turbo engine, Combined distortion, Phase angle, Stability, Mean relative temperature rise of face

1. Introduction

Most papers(Chalk,1997,Davis,1987,Hale,1998,Mazzawy, 1977,Tesch,1976) about inlet flow distortion discuss only the effect on compression system stability, and too many models have been built for compressors. The impact from other parts of engine is ignored. Of course, engine surge is mostly determined by the operation scope of fan and compressor. However, the bulks of combustor, turbine, nozzle and duct have crucial impacts on the stall margin of whole engine. Therefore, a new model for the whole engine from the inlet duct to the nozzle is developed to simulate the internal aerodynamics.

It is common physical phenomena to turbojet that suffers from combined pressure and temperature distortion. The effect is different from single pressure distortion or temperature distortion. It is more complicated. Diverse kinds of combined distortion have varied impacts on the engine, whatever the distortion intensity level, scale and overlap phase(Brithwaite,1979,Soeder,1984). Just like Mazzawy found on TF30. Therefore it is of interest how much the performance of an engine is affected by combined distortion. An applicable parallel compressor model is initially adopted in order to find the impact of combined distortion on compressor. But the calculated result does not conform very well to the experiment data under the condition that pressure and temperature are circumferentially non-uniform, especially in the case of small non-uniform scale of inlet flow. Thus it is necessary to build a new mathematic model to describe distortion based on the solution of whole aerodynamic equations set.

2. Nomenclature

F	force from engine part on the flow
ρ	air density
V	volume of control unit
t	time
S	surface area of control unit
c	victory of air flow
N	mechanical power
Q	heat quantity in unittime
C_v, C_p	specific heat

H	flight altitude km
M	flight Mach number
T	temperature distortion
P	pressure distortion
φ_{PT}	phase angle of combined distortion °
W	integrated distortion index %
δT	relative rise of temperature %
n_{2cor}	relative corrected speed of high pressure compressor %
α^{+}	scope of high temperature sector °
θ^{-}	scope of low pressure sector °
SM_{avai}	original stall margin %
α_W	sensitivity coefficient of total pressure distortion
α_T	sensitivity coefficient of total temperature distortion
$\alpha_{W,T}$	sensitivity coefficient of combined pressure and temperature distortion

Suffix:

θ	circumferential direction
x	axial direction
cr	critical

3. Method of simulation

3.1 Engine description

The turbojet engine in this paper is a gas generator which is composed of a six stages compressor, annular combustor, turbine cooled by air film, inlet and outlet ducts, as description in figure 1.

3.2 Introduction of the model

The mathematic model in this paper employed numerical simulation of two-dimensional Euler equations set based on the laws of mass, momentum and energy conservation. Those equations must be transformed into ordinary differential equations with a method of flux so that Runge-Kutta can be applied. More details have been described by Huang,2006. This model has been verified on a turbofan engine.

In this paper we study intake flow of turbo engine through the whole generator. The total flow passage along axial and circumferential directions was divided into small units. To the unsteady flow in every unit, flow is governed by three conservation equations as follows:

$$\left.\begin{aligned}
&\frac{\partial}{\partial t}\int_V \rho dV = -\oiint(\vec{c}d\vec{S}) + \int_V gdV \\
&\frac{\partial}{\partial t}\int_V \rho c_x dV = -\oiint \rho c_x(\vec{c}d\vec{S}) - \oiint \rho dS_x + F_x + \int_V c_x gdV \\
&\frac{\partial}{\partial t}\int_V \rho\left(c_p T + c^2/2\right)dV = -\oiint \rho\left(c_p T + c^2/2\right)(\vec{c}d\vec{S}) + Q + N \\
&\qquad + \int_V \left(c_p T + c^2/2\right)gdV
\end{aligned}\right\} (1)$$

Source items on the right side of equations are used to simulate the apply work of engine part on air flow. And to every computation station, momentum equations of circumferential and axial directions were built.

The distortion along radius is not considered due to the fact from experiment, in which radius distortion impact on engine stability is negligible for whatever pressure or temperature distortion.

3.3 Indices for combined distortion

Intake flow of turbojet engine, especially on a fighter, includes quite complex combined distortion flow. Such a flow field can be described in details by various distortion indices. To evaluate the distortion impact on the aerodynamic stability of turbojet, integrated distortion indices W, phase angle of combined pressure and temperature distortion sectors φ_{PT} are applied. W has been integrated with circumferential non-uniformity and area average turbulivity. δT_{cr} is the critical temperature jump which cannot surge the turbojet.

During the evaluation of engine stability, it is widely accepted that indirect rules are applied to judge the level of stability. Theses indirect rules include critical index of pressure distortion and the sensitivity coefficient of distortion. In fact, it is unusual that single pressure distortion or temperature distortion is observed in inlet flow. In most cases of actual application, they are combined with each other. Therefore it is essential to research on the sensitivity coefficient of combined distortion $\alpha_{W,T}$ in a synthetical way. On one hand, that coefficient indicates the extent to which engine stability affects by combined distortion. On the other hand, it represents the interrelationship between temperature distortion and pressure distortion. If $\alpha_{W,T}>0$, interaction intensifies. Else $\alpha_{W,T}<0$, they counteract. Sensitivity coefficient of combined distortion $\alpha_{W,T}>0$ can been defined as :

$$\alpha_{W,T} = \frac{SM_{avai} - (\alpha_W \times W + \alpha_T \times \delta T_{cr})}{\delta T_{cr} \times W} \tag{2}$$

4. Result and Discussion

All the simulation was selected on the ground: H=0m, M=0. Overlap phases of combined distortion includes $\varphi_{PT}=0°$, $\varphi_{PT}=90°$, $\varphi_{PT}=180°$. Figure 2 shows various combined distortion overlap phase angle.

4.1 Critical distortion index

According to the requirement from reference(Liu,2000), integrated total pressure distortion index W and temperature distortion index δT are applied at aerodynamic interface plane which is three times of the inlet duct diameter away from the first blade row. High temperature scope α^+ and low pressure scope θ^- are 180°, half of the inlet area. Thus the critical relative temperature rise δT_{cr} can be calculated out. The result is shown in figure 3~5.

It is obvious that the overlap phase φ_{PT} has a dramatic impact on the stability of engine. In figure 3, the critical relative temperature rise δT_{cr} at $\varphi_{PT}=0°$ is the lowest of all when engine operates at corrected rotation speed of 100%. In other words, it is the worst working condition when temperature distortion area coincides with that of pressure. Apparently, critical relative temperature rise δT_{cr} of 90°is higher than that of 0°and 180°.And δT_{cr} of 180°is higher than that of 0°. In addition, critical relative temperature rise δT_{cr} at 100% rotation speed is obviously greater than those at lower speed and equivalent W , despite of the overlap phases 90°or 180°, as shown in figure 4 and 5. So the available stall margin at design speed is larger than those at rotation speed of 90% and 85%.

In general, the critical relative temperature rise δT_{cr} descends with the intensification of pressure distortion W despite of the rotation speed and overlap phase φ_{PT}. Furthermore, δT_{cr} at 90-degree overlap phase is the largest of all. But it is different in details. The maximal temperature rise δT_{cr} decreases monotonously with the intensification of pressure distortion when overlap phase φ_{PT} equals 0. However there is a reverse climbing when low pressure distortion (W=4%~6%) is applied at inlet and overlap phase equals 90°or 180°. In other words, the engine can endure more serious temperature distortion than usual with the help of pressure distortion. That is clearly true when overlap phase equals 90°and rotation speeds is above 90%. The maximal increment of δT_{cr} above normal arrives at 1.2%, just like the peak point of red line in figure 3. In conclusion, there is some overlap phase of combined distortion to enhance the stability of engine as described by Davis,1991. Up till now, no detailed explanation has been issued for this phenomenon. A coarse conclusion cab be drawn that velocity triangle of rotor blade is improved when rotor sweeps over the overlap area periodically in spite of the increment of attack angle at low pressure sector and high temperature sector, thus the air separation on blade surface is delayed due to the common area, and so is the stage stall.

4.2 Sensitivity Coefficient of Combined Distortion

According to the definition of $\alpha_{W,T}$, simulation was conducted for sensitivity coefficient at different overlap phase (fig.6~fig.8).

Figure 6 provides sensitivity coefficient of combined distortion at a rotation speed of 100%. It is clear that some sensitivity coefficient is negative, which is favorable to the stability of engine. That is so-called “stability extension". Sensitivity coefficient $\alpha_{W,T}$ declines with the rising of overlap phase φ_{PT} in the beginning, and ascends later. It has a maximal value at φ_{PT} =0°, and minimal at φ_{PT}=90°. Sensitivity coefficient $\alpha_{W,T}$ at φ_{PT} =180° is larger than the former, but less than the latter. That reconfirms the engine stability at φ_{PT}=90°excels the rest at other phases. The most dangerous operation point appears at φ_{PT} =0°.

In general, combined distortion sensitivity coefficient is negative under middle pressure distortion intensity ($W\leq 8\%$) despite of the overlap phase. With the enhancement of pressure distortion intensity W, φ_{PT} climbs monotonously. Engine stability is put down after W exceeds 12% and φ_{PT} is positive. Stability extension steps down towards stability cutting.

Compared with curves at other speeds in figure 7 and 8, sensitivity coefficient of 100% n_{2cor} is far below those of other speeds. In fact, robustness against combined distortion at design speed is stronger than the others, and engine responses to distortion insensitively ($\alpha_{W,T}$ <0). The stability of turbojet is improved.

Figure 7 and 8 shows sensibility coefficient of combined distortion $\alpha_{W,T}$ at the rotation speeds of 85% and 90%. All coefficients are positive in spite of different overlap phase. The engine stability declines, especially at phase of 0°, the maximal stall margin is cut. At the speed of 85% n_{2cor}, coefficients of 90°and 180°are approximately equivalent, and stall margin is indistinctively affected by the expanding of overlap phase. It is interesting to point out that sensibility $\alpha_{W,T}$ at two non-design speeds fluctuate complexly, in spite that it increases monotonically at the speed of 100% n_{2cor} . In the case of φ_{PT} =90° and n_{2cor} =90%, sensitivity coefficient declines at first, and then climbs, as shown in figure 7. The lower rotation speed, the more equivalent for sensitivity coefficient of φ_{PT} =90°and φ_{PT} =180°. It is evident that engine stability primarily lies on the impact of pressure distortion at high speed, but is limited by temperature distortion much more at middle or lower rotation speed.

5. Conclusion

The maximal stall margin loss occurs when the distortion sectors of pressure and temperature overlap completely. This conclusion has been confirmed by Brithwaite and Soeder. If overlap phase is regulated properly, effect of one distortion can compensate the other, therefore, stall margin is expanded.

a) The overlap phase of combined distortion influences the engine stability remarkably. And most serious condition occurs up at overlap phase φ_{PT}=0° because of lower critical temperature rise than other phase.

b) For this engine, the available stall margin at design speed obviously excels those at off-design speeds regardless of the overlap phase. This conclusion can be drawn from its highest critical temperature rise and lowest sensitivity coefficient at all rotation speeds.

c) An ideal overlap phase exits which enhances the stability of engine. In this case, the critical temperature rise under low combined distortion (W=4%~6%) perhaps exceeds those under single temperature distortion when overlap phase is greater than or equals to 90°. The higher rotation speed, the better effect can be found.

d) Sensitivity coefficient of combined distortion becomes negative at the rotation speed of 100%, and stall margin extends. Therefore overlap phase plays an important role in that extension scope, and maximal stall margin is available at the phase of 90°.

e) Pressure distortion primarily confines the stability of engine at high rotation speed, and temperature distortion has more impact on the loss of stall margin at lower or middle speed.

6. Acknowledgments

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References

Brithwaite,W.M. and Soeder,R.H. (1979). Combined pressure and temperature distortion effects on internal flow of a turbofan engine, AIAA paper 79-1309, 1979.

Chalk,J.C. and Hale,A.A. (1997). A three dimensional compression system model using NPARC[R], AIAA-9720992, 1997.

Davis,M.W. and Brien,W.F. (1987). Stage-by-stage post stall compression system modeling technique[R], AIAA-8722088, 1987.

Davis,M.W. (1991). Parametric investigation into the combined effects of pressure and temperature distortion on compression system stability[R], AIAA -9121895, 1991.

Hale, A.O. and Brien,W.A. (1998). Three-dimensional turbine engine analysis compressor code (TEACC) for steady-state inlet distortion, Transactions of the ASME, *Journal of Turbo machinery,* 1998, 120 (7).

Huang, Shunzhou and HU, Jun. (2006). Model of the effect of inlet flow distortions on engine stability, *Journal of Propulsion Technology,* Vol.27 No.5 pp.426-430, 2006 .

Huang, Shunzhou. and HU, Jun. (2006). Investigation of the effect of combined distortion on engine stability, *Journal of Aerospace Power,* Vol.21 No.6 pp.1085-1091, 2006.

Liu,Daxiang. (2000). *Design hand book of aircraft engine*, Aviation Industry Publisher, Vol. 7 pp.2411-2417, 2000.

Mazzawy,R.S. and Banks,G.A. (1977). Circumferential distortion modeling of the TF30-P-3 compression system (PWA25448)[R], NASA CR2135124, 1977.

Soeder,R.H. and Bobula,G.A. (1979). Effect of steady-state temperature and combined distortion on inlet flow to a turbofan engine, NASA TM-79237, 1979.

Soeder,R.H. and Mehalic,C.M. (1984). Effect of combined pressure and temperature distortion orientation on high-bypass-ratio turbofan engine stability, NASA TM-83771, 1984.

Tesch,W.A. and Steenken,W.G. (1976). Blade and dynamic digital compressor program, Volume 1, J85 clean inlet flow and parallel compressor models[R], NASA, 1976.

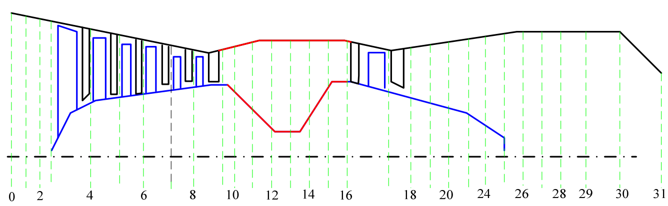
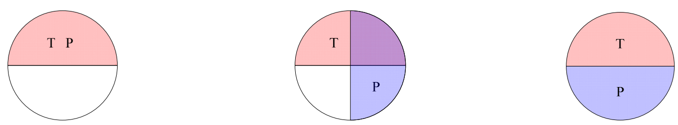


Figure 1. Engine model



a) φ_{PT} =0º b) φ_{PT} =90º c) φ_{PT} =180º

Figure 2. Various overlap phase of combined distortion

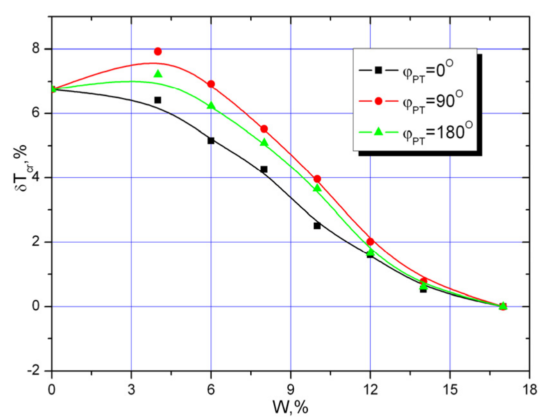


Figure 3. Characteristic of combined distortion at n_{2cor} =100%

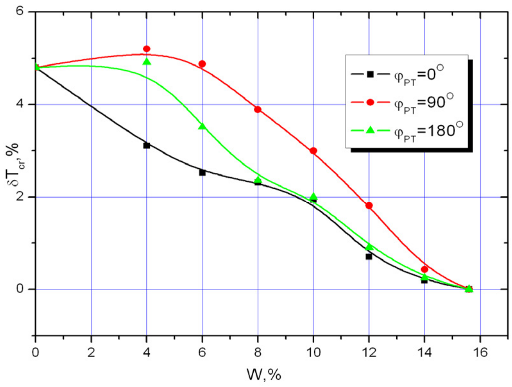


Figure 4. Characteristic of combined distortion at n_{2cor} =90%

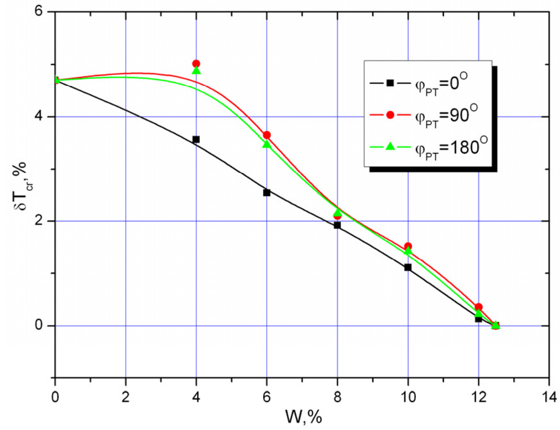


Figure 5. Characteristic of combined distortion at n_{2cor} =85%

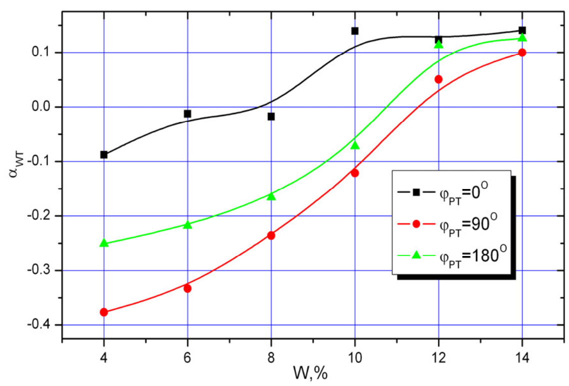


Figure 6. Sensitivity coefficient of combined distortion at n_{2cor} =100%

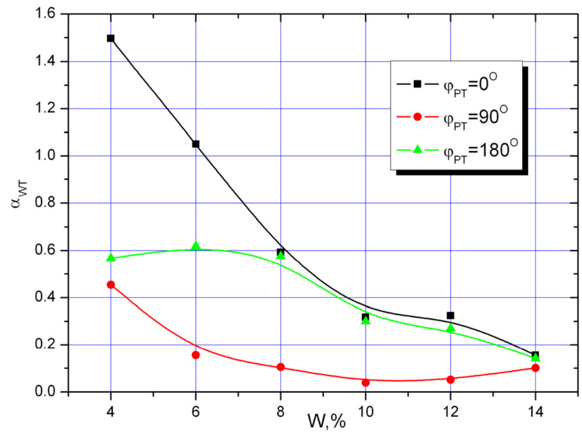


Figure 7. Sensitivity coefficient of combined distortion at n_{2cor} =90%

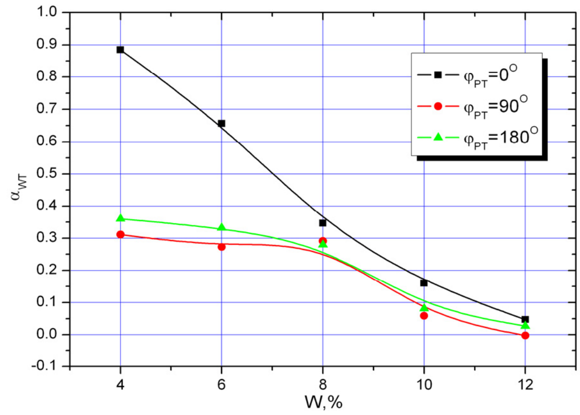


Figure 8. Sensitivity coefficient of combined distortion at n_{2cor} =85%