A STUDY OF DYNAMIC CHARACTERISTICS OF AXIAL COMPRESSION SYSTEMS BY HEAT ADDITION

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ABSTRACT

This paper presents an investigation of the dynamic effect of heat addition (e.g. by injection of fuel into the combustion chamber) on the operating point of the compression system which is of practical importance because of the consequence (rotating stall and surge) resulting from the operating point getting into the instability area.

The paper first developed a fluid dynamic model for a compression system consisting of an inlet duct upstream of an axial compressor, a plenum and an exhaust pipe with exit throttle valve. This model seems very similiar to Greitzer's[1],Tang's for quick motion of valve [2]and Tang's for change in the rotating speed [3],but the flow process here is now much more involved due to the heat addition into the air in the plenum.

Numerical results show that when the operating point is far away from the stall/surge limit,greater heat addition $\tilde{q}_f$,short duration ST, or greater parameter B will cause greater dynamic effect. Furthermore,the situation with the operating point originally in the hysteresis region presents special features: the operating point is easier to get into the stall/ surge limit due to heat addition. Again, the greater the heat addition ($\tilde{q}_f$)and the Greitzer parameter (B),the stronger the dynamic effect. Since the system may work with either rotating stall or surge,or in a steady condition, depending on heat addition $\tilde{q}_f$,parameter B and whether heat addition is stoped or not,there exist two critical values of B, i.e.: Bcr1 at which the transition from steady state work to rotating stall occures,and Bcr2 at which from rotating stall to surge takes place. The dependence of these two critical B on the main factors ($\tilde{q}_f$, ST, $\tilde{M}c$) is also detailedly investigated.

NOMENCLATURE

- a sound speed
- A flow through area
- B non-dimensional stability parameter,

$$B=\frac{U}{2a}\sqrt{\frac{Vp}{AcLc}}$$

- C compressor pressure rise
- Css steady state pressure rise
- Cx axial velocity
- F throttle pressure drop
- G non-dimensional number,defined as

$$G=\frac{L_T A_c}{L_c A_T}$$

- H semi-height of cubic axisymmetric characteristic,Fig.2a
- L effective length
- $\dot{m}$ mass flow
- N time lag constant for stalled part of the characteristic
- n rotational speed of the rotor
- p pressure
- Δp plenum pressure rise
- t time
- U mean rotor velocity
- Vp plenum volume
- W semi-width of cubic characteristic,Fig.2a
- ρ density
- τ compressor flow field time constant
- ψ $\Delta p/(\frac{1}{2}\rho U^2)$, total to static pressure rise coefficient
- ψ_o shut-off value of axisymmetric characteristic
- ω Helmholtz frequency
- $\tilde{q}_f$ heat addition for per unit of air mass in per second
- ST time period for heat addition

SUBSCRIPTS

- p plenum
- c compressor
- t throttle

SUPERSCRIPTS

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~ nondimensionalized variable

INTRODUCTION

The characteristic of a compressor has long been the subject of many investigators,because it is of importance almost in every stage of its development,even from the very beginning of its aerodynamic design to its various applications. While the prediction and investigation of the steady state characteristic of the compressor remains the topic of research work, the transient behaviour of the compressor has shared the attention of the designer and investigator due to recognization of the significance of the dynamic effect of the unsteady flow on the operation of the engine.

There is a long list of investigations devoted to the rotating stall and surge issue, inlet distortion problem[1],back pressure transients and so on . Exit valve motion may also cause unsteady flow[2] .And the speed change effect during an accelerating process has been investigated[3]. However,there has been very little information on the influence of heat addition on the behaviour of the compression system, which is obviously important for the operation of an engine,in particular, for example,when fuel injection is suddenly increased into the combustion chamber of a turbo engine.In practice,several important factors may act on the compression system simultaniously and the flow field will be determined by these factors.However in such cases the role played by heat addition may not be clearly examined. Consequently,there is a need to scrutinize the effect of heat addition on the transient behaviour of a compression system while keeping the other factors unchanged.The result of calculation will show how the operating point of the compression system varies duringa heat process;how it behaves when the initial points are in the hysteresis region.Two critical values of parameter B are identified: Bcr1 from steady flow to rotating stall, and Bcr2 from rotating stall to surge.The dependence of these two critical values of B is investigated in detail.

FLUID DYNAMIC MODEL

The compression system investigated consists of a compressor with an inlet duct, downstream followed by a plenum and an exhaust pipe with a throttle valve at the exit. The effective lengths of the equivalent ducts of the inlet and outlet duct are denoted by Lc and L_T ,respectively.

The inlet flow Mach number is supposed low enough to regard the flow as impressible.Also it is quite reasonable to treat the flow to be one-dimensional and inviscous.

The compression system used here, Fig.1, is

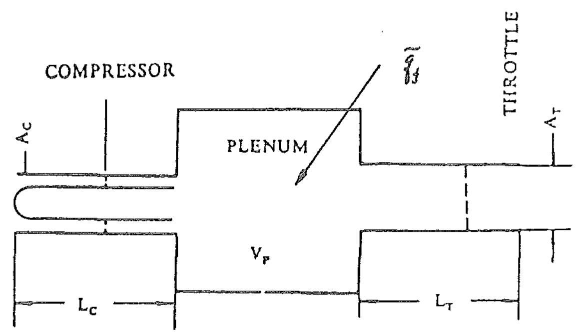


FIG.1 FLUID DYNAMIC MODEL

obviously very similiar to that in reference [4], but the present investigation is already for the heat addition to the air in the plenum which moves the operating point here and there on the compressor performance map.

GOVERNING EQUATIONS

Since there is no available equation to describe the flow dynamic process when the air is heated,the governing equations have to be developed first. It should be pointed out that the basic relations upstream and downstream of the plenum are the same as those for non-heated case with the exception that owing to the heat addition in the plenum,the pressure rise Δp_1 , upstream of the plenum will be different from that downstream of it, Δp_2 . Also the density of the air would not be uniform in the plenm,an average density is used. The above two pressure differences may be related through unsteady energy equation,momentum equation and equation of mass continuity.The process of deduction is rather tedious,and it is enough for the presentation to just put the resulting equations in the following.

$$\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} = B\,(\tilde{C} - \Delta\tilde{p}_1) \tag{1}$$

$$\frac{d\tilde{\dot{m}}_T}{d\tilde{t}} = \frac{B}{G}\left(\Delta\tilde{p}_2 - \frac{1}{2}F\,\tilde{\dot{m}}_T^{\,2}\right) \tag{2}$$

$$\frac{d\tilde{C}}{d\tilde{t}} = \frac{1}{\tau}\,(\tilde{C}_{ss} - \tilde{C}) \tag{3}$$

$$\frac{d\tilde{\rho}_m}{d\tilde{t}} = \frac{2BA_cL_c}{A_vL_v}\,(\tilde{\dot{m}}_c - \tilde{\dot{m}}_T) \tag{4}$$

$$\frac{d\Delta\tilde{p}_1}{d\tilde{t}} = f_1(B, L_c, A_v, A_c, G, \Delta\tilde{p}_1, \Delta\tilde{p}_2, \tilde{\dot{m}}_T, \tilde{\dot{m}}_c, \tilde{q}_f, \tilde{\rho}_m) \tag{5}$$

$$\frac{d\tilde{p}_2}{d\tilde{t}} = f_2(B, L_c, A_v, A_c, G, \Delta\tilde{p}_1, \Delta\tilde{p}_2, \dot{\tilde{m}}_T, \dot{\tilde{m}}_c, \tilde{q}_t, \tilde{P}_m) \qquad (6)$$

It is seen from the above equations that although the equations are complicated, the procedure for solution is the same as that for the non heat addition case.

CHARACTERISTIC OF COMPRESSORS

Before computation of the equations, the steady-state characteristic of the compressor should be specified. The equation arises as to what characteristic of the compressor should be employed: a particular one or a generalized one? One might calculate the equations for an existing compressor characteristic to see the basic features du e to heat addition. However, there is a difficulty to experimentally obtain the parts of the characteristic from the onset of rotating stall to the fully developed rotating stall point and recovery from the stalled condition to the unstalled flow. On the other hand, adoption of a generalized characteristic is reasonable since the present investigation is concerned about the basic features of the transient behaviour instead of that of a particular compressor. This idea leads us to the composition of a generalized characteristic of a compressor, which consists of three parts:

An axisymmetric cubic characteristic for the unstalled part and reversed flow:

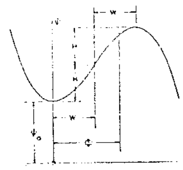
$$\psi = \psi_0 + H\left[1 + \frac{3}{2}\left(\frac{\Phi}{W} - 1\right) - \frac{1}{2}\left(\frac{\Phi}{W} - 1\right)^3\right] \qquad (7)$$

A relation between ψ and Φ for the rotating stall part; Φ being Cx/U.

$$\psi - \psi_{00} = D\left|(\Phi - \Phi_{00})^p\right| \qquad \Phi \geq \Phi_{00}$$
$$\psi - \psi_{00} = -D\left|(\Phi_{00} - \Phi)^p\right| \qquad \Phi < \Phi_{00} \qquad (8)$$

Where, D and P are some constants, ψ_{00} and Φ_{00} are the values of ψ and Φ at $\Phi = W$

This generalized characteristic is shown on Fig.2, where both Galerkin solution and the exact solution are also shown. It is obvious from the figure that the relation of equation (8) is more near to the exact solution than Galerkin solution yet it is simpler than the numerical exact solution. Adjustment of the constant p may change the rotating stall curve. It can be seen easily that the system hystersis appears naturally when using the rotating stall curve since it is set by the stability of the system at the various intersection points of the throttle and the compressor curves, Corresponding to the point at the axisymmetric curve and the point at the rotating stall curve . There can thus be a difference in the throttle setting at which transition from unstall to stall and from stall to unstall occur. In other words, the mass flow at which compressors unstall is (considerably) higher than that at which they stalled.



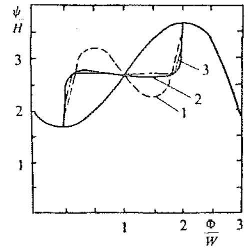


FIG.2a NOTATION FOR H,W FIG.2b CHARACTERISTIC
1.GALERKIN SOLUTION
2.EXACT SOLUTION
3.SIMPLIFIED RELATION

While the form of characteristic has been generalized, the parameter ,H and W, are taken to approximate an existing 3-stage compressor characteristic, thus ψ_0 =0.4, W=0.24 D=H/W(p=8 in the calculation). The peak point of this characteristic is then at Φ =0.48with the pressure rise of ψ =1.28.

NUMERICAL RESULTS

General Trends. First we will examine the general trend when the air in the plenum is heated, the initial operating point being at a place far from the surge or stall limit, Fig.3.

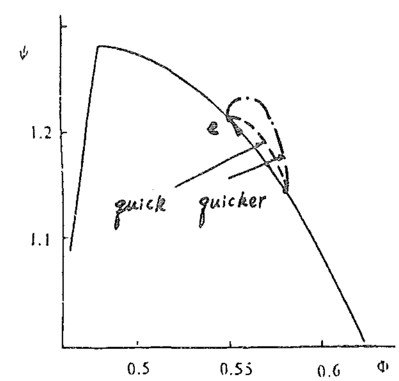


FIG.3 GENERAL TREND

When heat addition is achieved in a quasisteady manner, the operating point will go up just along the characteristic without notable deviation. However, when the air is heated quickly, the operating point will go above the steady-state one with some deviation, and finally reach the same point, e. The deviation will become greater for the greater rate of heat addition. Nevertheless, the final operating point is the same for the different processes as long as the final value of the non-dimensional heat addition, $\tilde{q}_f$, is the same. Physically, when the air in the plenum is heated with $\tilde{q}_f$ the density of the air in the duct downstream of the plenum will become smaller, and the mass flow rate through the compressor is decresed. When the air is heated quickly, the mass will decrease quickly too, causing the operating point above the steady-state characteristic. Next, suppose the initial point is at somewhere near to the surge/stall point, the result is shown in Fig.4 to Fig.6.

Fig.4 is for the different values of B, the

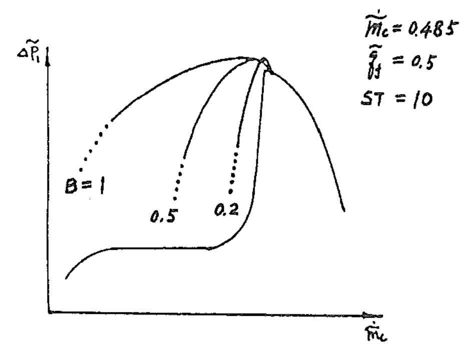


FIG.4

$\tilde{q}_f$ and ST being the same. With the greater B, the operating point will go upper, meaning that the system has greater dynamic effects.

Fig.5 shows the heat addition effect for the

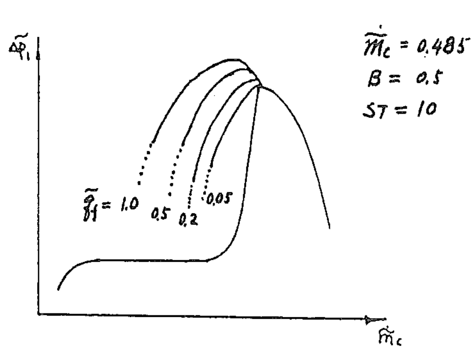


FIG.5

system with the same value of B. Again we see that a greater value of $\tilde{q}_f$ gives rise to a greater dynamic effect on the compression system.

Fig.6 gives the same thing as from Fig.5, but

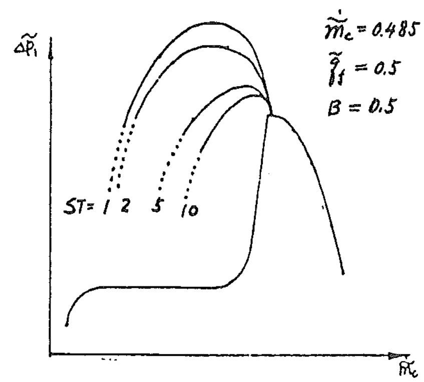


FIG.6

from another point of view.

Now the question arises as to what will happen since the operating point has got into the instability region, this will be answered in the next paragraph.

Hysteresis Region. This region is of interest because the pressure rise is higher and the efficiency is better for the point in the region, but the operating point is easier to get into the instability region, since the region is very near to the surge/stall limit. We will present the numerical result in an order of the value of B from small to large. The initial point is at $\dot{\tilde{m}}_c$ =0.485, the instability limit being at $\dot{\tilde{m}}_c$=0.48. That is to say that the operating point was at a place some way from the instability limit, the compression system was working in a steady-state regime before heat is added into the air. The amount of heat addition and the rate of heat addition are all kept the same for this series of events: $\tilde{q}_f$ =0.05 and ST=10. Fig.7 shows the situation

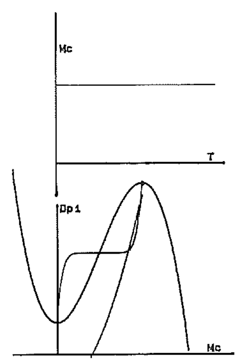


FIG.7

when B is very small,say,B=0.18. In this case the operating point moves just a short way that it can not get across the instability limit,the system works in the steady-state flow regime. With the increase in the value of B, e.g.B=0.5,the operating point first got across the limit and then goes down and runs around the intersection of the characteristic and the throttle line,finally working at a point near to that intersection with rotating stall,Fig.8

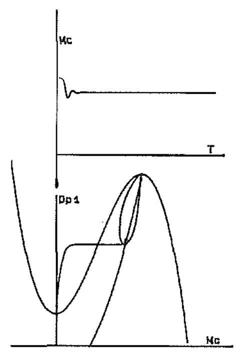


FIG.8

For a value of B great enough,say,B=0.8, the operating point will go around the peak point and the intersection,forming a limit cycle of oscillation--- surge occurs,Fig.9.

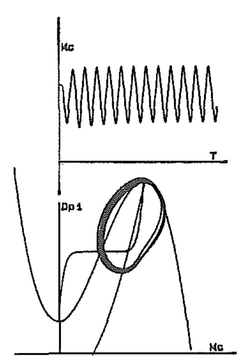


FIG.9

Thus we see that in the hysteresis region, even with the same heat addition (amount and rate) the result will be quite different,dependent upon the value of parameter B.

Critical Values of B. From the above mentioned result it is clear that when the air in the plenum is heated there are three basic kinds of system reponses. Therefore, there are two critical values of B at which the system behaviour will change from one type to another type. They are Bcr1, at which the compressor will change its work from steady-state flow condition to rotating stall,and Bcr2,at which from rotating stall to surge. As one has already noticed that for the original case (without heat addition) there is only one value of B to judge the instability mode -- rotating stall or surge. Now when the air is heated there is an additional critical value of B to distinguish rotating stall or steady-state flow.

Variations of the Critical Value of B with Parameters Concerned.The above-mentioned result is for the situation when the operating point at first is at $\tilde{\dot{m}}_c$=0.485. However,there is a whole region ,i.e,hystersis region,with the operating point originally in which the compression system might have similar behaviours. Does it really exhibit the same behaviour or is there something different? To answer the question,we have to observe the response of the system over the whole range of the hysteresis region.

Response to Small Heat Addition. Fig.10 shows

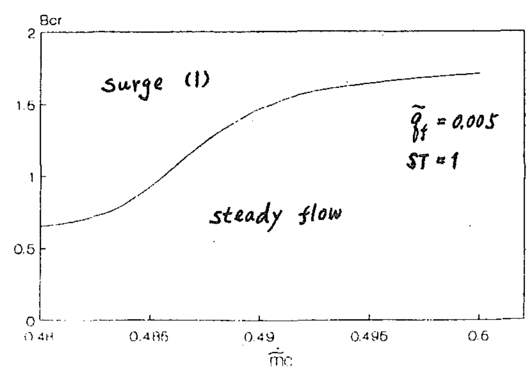


FIG.10

the variation of Bcr with the initial position of the operating point when the amount of heat addition is very small, say, $\tilde{q}_f$=0.005 and the heat is added at a rate of ST=1.In this situation there are two zones with a curve separating them : steady flow zone and surge zone. There is no rotating stall zone. This result can be understood considering that the amount of heat addition is very small, so that the system has to have dyanmic response strong enough for its operating point to reach the instability limit. It follows that when $\tilde{q}_f$ is very small,the system has to have parameter B great enough for operating point to get into the instability area,and for that value of B the instability mode in which the system would respond is already surge rather than rotating stall.

With the increase in the mass flow rate the distance between the initial position of the operating point and the instability limit become long,the value of B at which the operating point could touch the instability limit has to be increased to cause even great dynamic effect. That's why the critical value of B increases with mass flow rate. After heating stops the system would remain in surge mode in the zone marked by (1).

Response to Middle Heat Addition. Keeping ST=1, with heat addition $\tilde{q}_f=0.5$, there are essentially three zones (Fig.11) corresponding

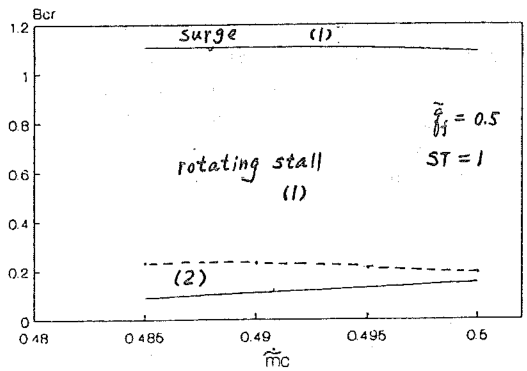


FIG.11

three manners in which the system would respond. Examining the variation of the system behaviour from small B to great B, the system first works in steady flow regime, then, roughly at B=0.1~0.2, the system response would change from steady flow to rotating stall. At approximately B=1.1 transition from rotating stall to surge occurs. This sequence of events is quite ordinary. Addition of middle amount heat makes dynamic effect strong enough for the system operating point to arrive at the instability limit at small value of B that once the operating point gets into the instability area the compressor would work in rotating stall. After heating stops the system would remain in rotating stall in the zone labelled with (2), but it would recover to work in steady state flow regime in the zones labelled with (1).

Response to Great Heat Addition. Increasing heat addition to $\tilde{q}_f=1.0$ will make some change in the system response. In this situation, the

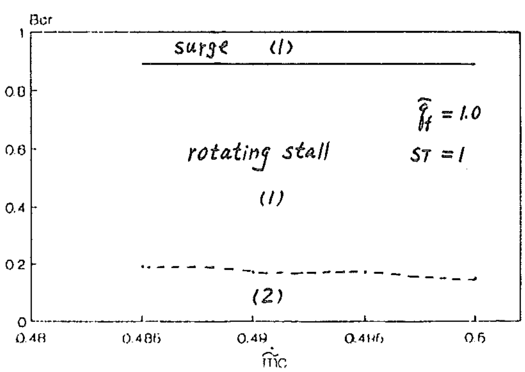


FIG.12

zone for steady-state flow regime disappears. The dynamic effect of the heat addition is already so great that at very small value of B the operating point may get into the instability region, resulting in working in rotating stall mode. After heating stops, the system would still work in rotating stall in the zone labelled with (2), but would recover to steady-state flow regime in the zones labeled with (1), Fig.12.

CONCLUSIONS

1. The influence of unsteady heat addition on the axial compression system has been investigated, the unsteady heat addition is shown to have important effects on the system dynamic response.

2. The response of the system mainly depends upon the heat addition law (increasing heat addition rate and final heat addition rate, as expressed here as ST and $\tilde{q}_f$) and the B parameter. Usually the greater the value of B, the greater the dynamic effect on the system operation for a given set of ST and $\tilde{q}_f$; also, the greater the heat addition rate ($\tilde{q}_f$) and the greater the heat addition increasing rate, the greater the dynamic effect for a given B.

3. For the opreation with the initial position of the operating point in the hysteresis region, heat addition may cause the operating point to get into the instability area, the response of the system could be rotating stall or surge as well as steady-state flow according to the condition of $\tilde{q}_f$, ST, and B.

4. There exist two critical values of B: Bcr1 at which transition of the system response from steady-state flow to rotating stall occur and Bcr2 at which that from rotating stall to surge happens.

5. The variations of the critical value of B with variaous parameters are also investigated

REFERENCES

1. E.M.Greitzer, "Review-Axial Compressor Stall Phonomena" Journal of Engineering for Power, Vol.102, June, 1980.

2. G.C.Tang, "An Investigation of Dynamic Breaking in the Compressor Stall/Surge Limit" Proceedings of 5th International Symposium on Unsteady Aerodynamics and Aeroelasticity of Turbomachines and Propellers.

3. G.C.Tang, "Basic Features of Speed Induced Transient Behaviours of Axial Flow Compressors", ASME paper 90-GT-211.

4. E.M.Greitzer, "Surge and Rotating Stall in Axial Flow Compressors", Journal of Engineering for Power, Vol.98.