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AERODYNAMIC CHARACTERISTICS OF GENERAL AVIATION AT HIGH ANGLE OF ATTACK WITH THE PROPELLER SLIP STREAM

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16. Abstract

The aerodynamic characteristics of the FA-300 business aircraft at high angle of the attack with the propeller stream are described. The Fa-300 offers two types, Fa-300-700 for 340 HP, and -710 for 450 HP of the engine. The effects of the propeller slipstream on the high angle of the attack are discussed.

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1. INTRODUCTION

Aerodynamic characteristics at high angle of attack are some of the important safety related subjects for small business airplanes as well. It is vitally important for the small business airplanes to be able to recover from a stall without going in to a spin or bad divergence movement.

The majority of the small business aircraft is propeller aircraft. In the case of propeller aircraft, the flow of air around the aircraft becomes far more complex during the high angle of attack due to the influence of the propeller slip stream. In this essay, aerodynamic characteristics of FA-300 business airplanes at high angle of attack with the propeller slip stream are discussed based on the experience gained through the developmental process of FA-300.

FA-300, twin engine business aircraft jointly developed by Fuji Heavy Industries and a US aircraft manufacturer through an international joint development agreement, has two models. They are FA-300-700 (340 HP model) and FA-300-710 (450 HP model). The 710 model with higher engine output has a variety of changes made as shown in Fig. 1 compared to the 700 model. These changes were made necessary primarily due to the increased influence of the propeller slip stream at the high angle of attack with some exception.

2. GENERAL CHARACTERISTICS AND INFLUENCE OF PROPELLER SLIP STREAM

Propeller slip stream which is the rear flow of the propeller is high in flow velocity compared with the free flow. At the same time, it (propeller slip stream) rotates toward the direction of the propeller rotation. In the case of the simple substance of the propeller, increase in the dynamic pressure $\Delta q_s/q$ and the average rotation angle θ toward the free flow in reference to the thrust coefficient which is shown as

$$T_c = \frac{T}{q s_D}$$

(T: thrust of the propeller, q: dynamic pressure of the free flow, sD: square measurement of the propeller disc) can be calculated according to the following formulas:

$$\frac{\Delta q_s}{q} = T_c$$

$$\theta = \frac{3}{\pi}\left(\frac{v_0}{nD}\right)\frac{T_c}{2+T_c}$$

(vo: velocity of free flow, n: rpm of the propeller, D: diameter of the propeller)

For example, if Te = 2.52, vo/nD = 0.33, then the dynamic pressure will be equal to 3.5 times the free flow, and the rotation angle will be approximately 10 degrees.

In reality, however, the above figures will be changed a little due to the influence of the nacelle or the main wings on the slip stream. As for an example, a measured figure of a small single engine aircraft, Te = 2.52, vo/nD = 0.33, is shown. Fig. 2 shows the comparison of the result obtained by Fink et al. through a wind tunnel test (9) of a test aircraft. The same figure shows the figure of Te = 0 (condition without propeller) and Te = 2.52 on the dynamic ratio in reference to the free flow and the side direction distribution (the figure at 0 degree angle of attack) of the blow down angle at the position of the horizontal tails. Compared with the calculation figure of the single substance of the propeller (dynamic pressure ratio, 3.5; rotation angle, 10 degrees) as descried earlier, the peak figure of the dynamic pressure ratio shows almost the same level. Yet, the blow down angle (in other words, the vertical directional element of the rotation angle) shows approximately one half (of the figure) at the starboard side. Influence of the slip stream on the aeronautical characteristics of small airplanes at the time of low angle of attack includes the following: (1) Increase in dynamic lift through increased dynamic pressure of the main wings, (2) changes in lengthwise rocking moment and lengthwise stability by the changes in dynamic pressure and blow down toward the horizontal tails, and (3) generation of sway moment through generation of side-flow toward the vertical tail. Among the above listed items, generation of the sway moment in particular is associated with the take-off difficulty experienced by single engine aircraft. In addition to that, reduction in the upper angle of the wings at the time of sliding as well as generation of side force are also well known.

3. AERODYNAMICS CHARACTERISTICS AT THE TIME OF HIGH ANGLE OF ATTACK CAUSED BY PROPELLER SLIP STREAM

Influence of the slip stream upon the high angle of attack is examined next.

3.1 Wing drop

Wing drop is the phenomenon where the aircraft becomes tilted either to the right or to the left through the exfoliation of the air flow at the upper surface of the main wings. In the case of propeller airplanes, the phenomenon of wing drop does not develop at the time of stall when the output of the engine is reduced. It sometimes develops at the time of stall when the engine output is increased. The slip stream will rotate toward the right if the propeller rotation is toward the right. Accordingly, the local angle of attack of the left main wing within the slip stream will be increased, while the same on the right main wing will be decreased. Accordingly, exfoliation of the air flow at the left main wing will take place as the condition of stall becomes nearer causing the phenomenon of the wing drop toward the left. Shown in Fig. 3 are data obtained by Fink et al. during a wind tunnel test (9) of a small test model aircraft. It shows the influence of the propeller slip stream concerning the changes in side-rocking moment in reference to the angle of attack. In this example also, the phenomenon of wing drop is generated at the time of a stall in case the propeller slip stream is in existence through the power-on condition. Th aircraft will sharply tilt toward left from the point indicated by a white arrow. If the angle of attack is further increased, then the phenomenon of wing drop toward the right will be seen (shown in a black arrow). The reason for the tilt toward the right may be due to asymmetry in the exfoliation of the main wings at the part other than the slip stream. Exfoliation is considerably difficult at the right side wing due to the practical reduction in the attack angle due to the slip stream of the base part of the wing. As the attack angle is increased, exfoliation is spread toward the direction of the outer wing. Consideration must be given not only to the initial wing drop but also the secondary wing drop. Incidentally, the stall characteristics obtained through the actual flight test are not controlled simply by the changes in the side-rocking moment. Instead, they must be considered as the result of the combined changes in both the side-rocking moment and the sway moment.

The case of twin-engine aircraft is far more complicated than the single-engine aircraft as far as the influence of the slip stream is concerned. Fig. 4 shows a typical stall pattern at the time of power-on. In this case, swing drop toward the right takes place due to the exfoliation between the right nacelle and the fuselage followed by a sharp tilt to the left caused by the exfoliation of the outside of the nacelle of the left wing as the attack angle is increased.

In the case of FA-300, attention has been paid to the above points. In a special case in which an intentional pilot error is experimented at the power-on stalling during the landing phase, the problem of the wing drop has been experienced.

Characteristics of the initial stall in the case of FA-300 are quite fine. That is to say that an ideal stall pattern in which exfoliation is gradually progressed from the base of the wings has been demonstrated. At the time of the power-on also, the above nature seems to be at work hardly generating the tilt at the time of a stall. In the stall condition with the function of one engine terminated, the tilt angle was found to be less than ten degrees. This is an extremely outstanding flight test result. Yet, FAA made a rather negative remark on the moderate characteristics as described above and pointed out during the flight test in USA that a stall could not be clearly recognized. Accordingly, FAA requested that the elevator should be pulled up to the stopper and that the method of the pulling of the elevator had to be at the speed reduction ratio of 3 - 5 kt/sec (known as the aggravated control) instead of recovering from a stall condition. Therefore, the attack angle reached a considerable figure in reference to the initial stall, and the problem in which it does not appear during the initial stall has developed. Nevertheless, the degree of the wing drop was found to be rather small in the 700 model with 340 HP engine. Thus, tilt control of the aircraft was possible. However, in 710 model whose engine output is raised to 450 HP and the propeller diameter is increased from 81 inches to 93 inches, the wing drop became uncontrollably high at the stall during the landing phase when the air speed was low (the power effect becomes high). The engine of the 710 model turns toward the left, and a strong wing drop toward the right was generated. In other words, the right nacelle outer wing was exfoliated by the strong blow-up of the propeller slip stream generating the rightward tilt. Power-on wind tunnel tests as well as flight tests were conducted in order to find counter measures of the wing drop. The following measures have been discussed as the possible solution to the problem:

A stall strip was installed to the front edge of the left side outer wing in order to relatively weaken the left wing.

A fence was installed at the outer wing in order to make the outside area of the outer wing difficult to exfoliate while aiming to secure the function of eruron *. (Fig. 5)

As the result of the above measures, the problem of wing drop was eased considerably making it possible to keep the tilt within ten degrees even during the aggravated control.

In recent years, more and more business airplanes are adopting the system called counter rotation in which the right and the left propellers are rotated toward the opposite direction.

3.2 Changes in air flow around the tails by the propeller slip stream at high angle of attack

Fig. 6 shows the dynamic pressure distribution of air flow in the vicinity of the tails at the presence of the slip stream. The information was obtained by a power-on wind tunnel test of a 13 % test model of the FA-300 model. At the low angle of attack (alpha = 5 degrees), the propeller slip stream as a whole is shifted toward the right although it is almost symmetric. At the high angle of attack (alpha = 20 degrees: the entire main wings nearly totally exfoliated), on the contrary, an extremely complicated air flow is formed. The point to be noticed is the positional relationship between the slip stream and the wake *. In both the port and the starboard sides, the slip stream is winding up the exfoliation wake of the main wings to the left. Accordingly, the port side of the horizontal tails enters the slip stream, and the starboard side enters the wake. The air flow therefore is asymmetric. Incidentally, the slip stream as a whole is weakened influenced by the exfoliation flow.

Fig. 7 shows the data obtained by the wind tunnel test (11) of a small twin engine model (mock up) conducted by Fink and Freeman. Fig. 7 shows the distribution of the dynamic pressure ratio and the blow down angle of the air flow at the position of the horizontal tails. The figure also shows the changes made during the power-on period as well as the comparison with the figure of the power-off period.

At the time of flap-up condition (Fig. 7a), right-left symmetry is observed at the low angle of attack (alpha = 0 degree). (Slip stream is slightly shifted toward the right.) Not much changes are observed in the blow-down angle as well. At the high angle of attack (alpha = 16 degrees), right and left become asymmetric. Above all, the blow-down angle of the port side shows the increase of ten degrees compared to the power-off condition. This is due to the asymmetric exfoliation caused by the slip stream. At this time, exfoliation between the fuselage and nacelle has not taken place yet, and the dynamic lift is considered still high.

At the time of flap-down condition (Fig. 7b), right-left asymmetry at the high angle of attack is particularly significant. In the case of the flap-down, right and left are asymmetric even at the low angle of attack. (This is due to the strong interference effect of the flaps toward the slip stream.) At the high angle of attack, the port side shows the blow-down condition with high dynamic pressure, while the starboard side shows the blow-up condition with low dynamic pressure. Local angle of attack at a part of the port side in particular is as high as 20 degrees. If the local angle of attack is high, then local exfoliation will be developed at the upper surface of the horizontal tails.

As described above, air flow in the vicinity of the tails shows great changes at the time of the high angle of attack due to the presence of the propeller slip stream. The changes in air flow bring about additional problem in the characteristics at the time of the power-on high angle of attack that was not present at the time of power-off.

3.3 Pitch•up

The term pitch•up means the lifting of the nose. If the condition of pitch•up is developed at the high angle of attack in particular, the attack angle is further escalated bringing about a dangerous situation. Therefore, this is one of the characteristics that must be avoided by all means. The cause of the pitch•up is either the development of the pitch•up moment of the main wings themselves as seen in the case of the receded wings or the development of the pitch•up moment by the changes made to the air flow toward the horizontal tails. As described in the previous paragraph, air flow in the vicinity of the horizontal tails of small propeller airplanes changes significantly because of the presence of the propeller slip stream. Sometimes, this could become the cause of the pitch•up.

The example of the previous paragraph as seen in the twin engine propeller airplanes indicates the generation of the pitch•up moment at the port side by the high level of blow-down with high dynamic pressure at the time of power-on high angle of attack, while the starboard side generates the pitch•down moment caused by blow-up. Needless to say, the both sides cancel each other. However, in case the degree of right-left asymmetry becomes more intense resulting in stronger blow-up at the starboard side, the upper surface of the horizontal tails becomes exfoliated. Thus, increase in pitch•down moment cannot be expected. Furthermore, lowering of the dynamic pressure is also added. The final outcome is the generation of the pitch•up.

The horizontal tails of FA-300 are positioned at the middle part of the vertical tail. (It is called the mid-tail). In the case of the T-tail in which the horizontal tails are fixed to the upper part of the vertical tail, pitch•up could be developed through the entrance of the main wings into the wake that is completely exfoliated. Yet, in the case of the normal mit-tail, the above described situation does not develop under normal circumstances because the wake is not large enough as the wake of the main wings passes through the horizontal tails. In fact, no pitch•up was experienced even at the time of aggravated control.

However, the condition of the pitch•up developed at the time of landing when the power effect was the highest in the case of the power-on stalling test as the aggravated control was practiced. The attitude of the airplane either remained the same or stayed at a slight nose up condition even after pulling the elevator all the way to the stopper. Successful recovery from the stalled condition could not be made unless the control stick was pushed forward.

The degree of the above problem was not too severe in the case of the 700 model which has less HP. Therefore, the above described problem was correctly remedied through the establishment of the proper limit of the rear center of gravity as well as the maximum elevation angle of the elevator. In the case of the 710 model with much greater HP, however, it was necessary to remodel the horizontal tails and the elevator.

Said pitch•up is caused by the changes in the air flow in the vicinity of the horizontal tails by the propeller slip stream. Due to the blow-up by the slip stream, a part of the upper surface of the horizontal tails becomes exfoliated in the condition of high angle of attack with the elevator raised to the maximum. Consequently, the condition of the elevator•lock was also developed.

In order to counter the above problem, wing span of the horizontal tails was extended so that the slip stream with high dynamic pressure that is located at the outside of the wake on the port side may be caught. Furthermore, the span of the elevator was shortened so as to lower the effect of the elevator at the high angle of attack. It was done so in order to prevent the excessive attack angle by erroneous operation of the pilot. (Fig. 8) Accordingly, the problem of the pitch•up was completely solved.

Fig. 9 shows the time history data obtained as the result of the stall characteristics test of the 710 model after the above measures have been applied. It shows no pitch•up in spite of the exercise of the aggravated control even at the most severe landing condition or at the time of the power-on stalling at the far end of the center of the gravity. Furthermore, the data indicate that the bank angle can be controlled within ten degrees.

4. AN AFTERWORD

It is believed that the ratio of the propeller airplanes including small airplanes for business use as well as ATP aircraft will maintain the current level in the future. Influence of the propeller slip stream has been the target of the research activities since the golden era of the propeller aircraft. The research activities of the same subject has been conducted as a part of the V/STOL research also. (16) Yet, further research of the subject matter at the time of the high angle of attack is needed. Movement and influence of the propeller slip stream are difficult to estimate. Study of the subject matter through the calculation of the aerodynamics may be expected in the future (18). Yet, it is necessary to conduct the wind tunnel tests under the power-on condition in the design process in order to fully grasp the condition and characteristics of the air flow.

Content of the data on FA-300 was compiled by the authors partially from the works conducted by the members of the FA-300 development room.

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[Translator's note]

※ mark indicates phonetic translation of Japanese words.

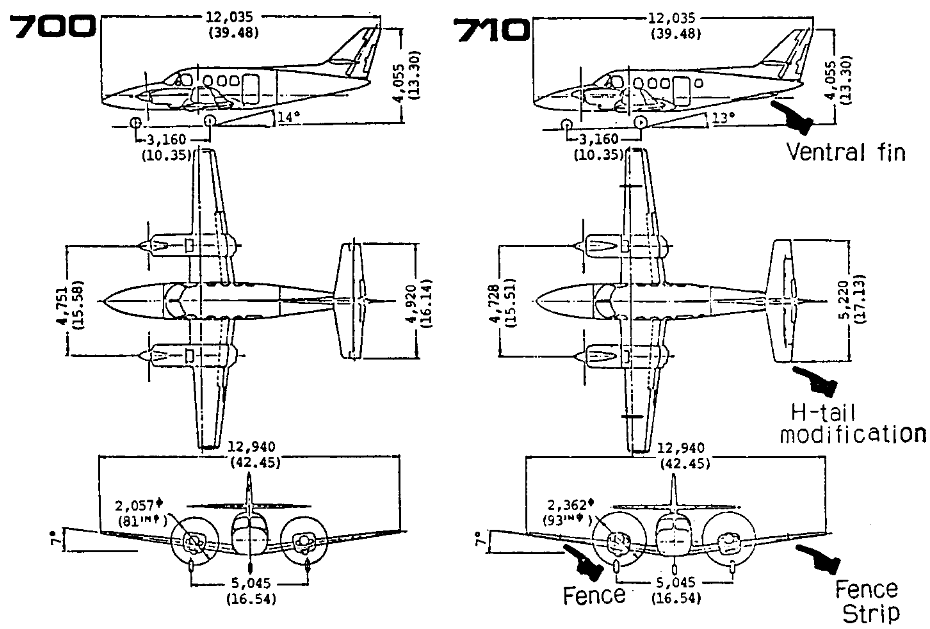


Fig 1 第1図 FA-300 700 型および 710 型の三面図

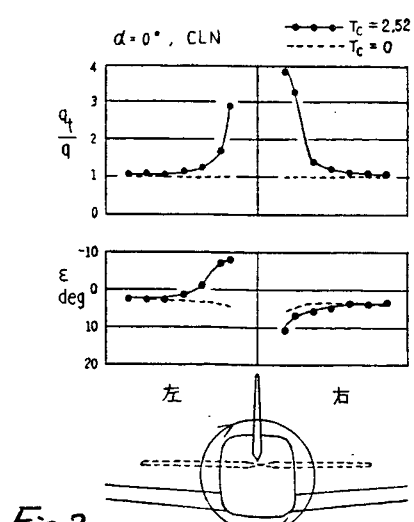


Fig.2
2図 小型単発機の水平尾翼位置の気流に対するプロペラスリップストリームの影響

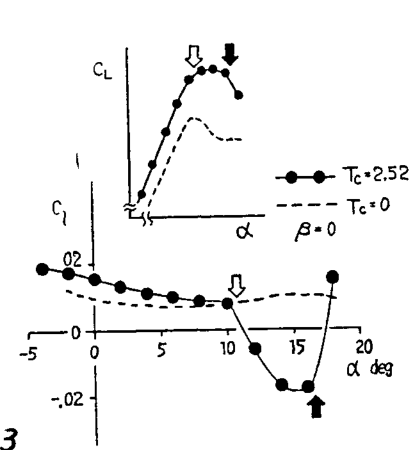
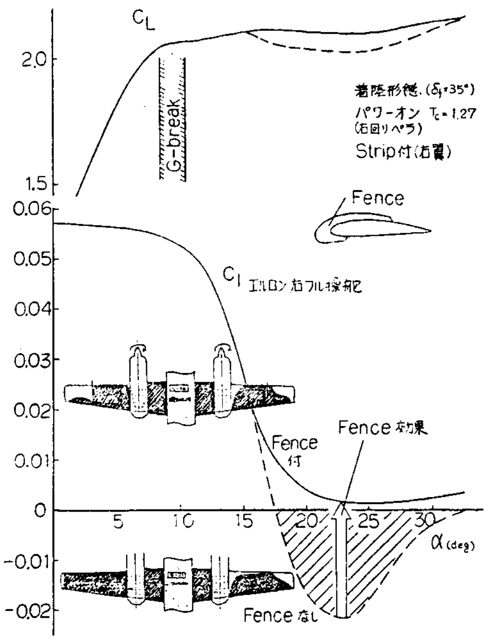


Fig.3
第3図 小型単発機におけるプロペラスリップストリームによるウイングドロップの発生



第5図　FA-300 13% 模型パワーオン風試結果　主翼フェンス効果

Fig.5

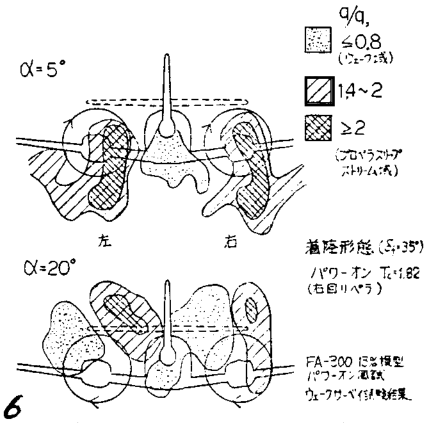


Fig. 6

第6図　パワーオン（右回りペラ）時の尾翼付近の気流状態（動圧分布）

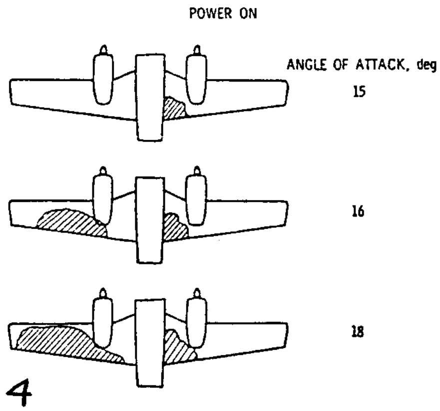
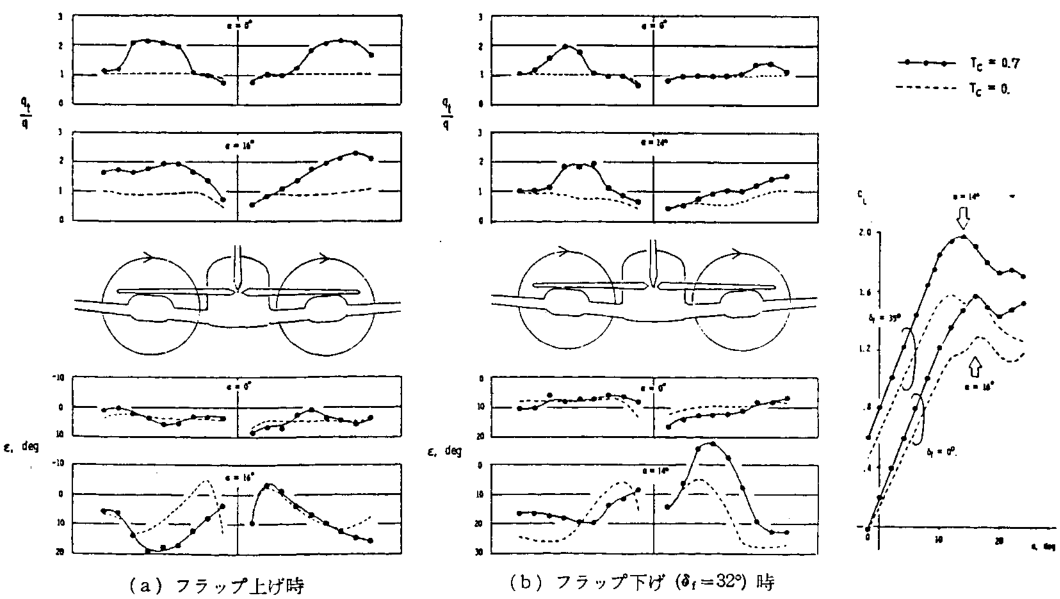


Fig. 4

第4図　双発プロペラ機のパワーオン時の失速パターン[1]（右回りペラ）



（a）フラップ上げ時　（b）フラップ下げ（δ_f=32°）時

第7図　小型双発機のプロペラスリップストリームによる水平尾翼位置気流の変化
パワーオン／オフ時の水平尾翼付近の動圧比，吹下し角分布の比較

Fig. 7

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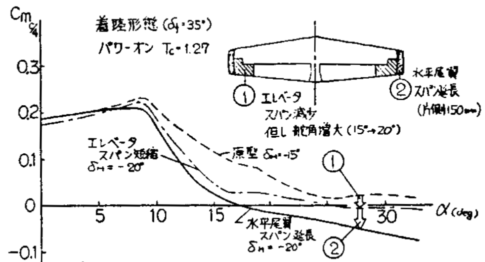

Fig. 8

第8図　FA-300 風試結果—ピッチアップ対策
エレベータ上げいっぱい時ピッチング
モーメント

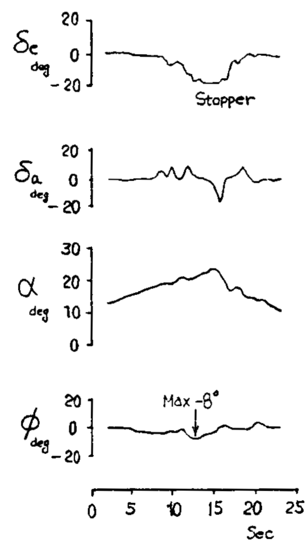

Fig. 9

第9図　FA-300 710 型パワーオン失速特性（着陸形態，
重心最後方位置，Aggravated control)