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Wind-Tunnel Measurements of the E-8C Modeled with and Without Winglets

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I. Introduction

THE joint surveillance target attack radar system (Joint STARS) E-8C aircraft, pictured in Fig. 1, is a long range, medium endurance, battle management platform using its AN/APY-3 phased-array multimode radar to locate and track moving vehicles across a very wide area. Joint STARS was built using a Boeing 707 aircraft and retrofitted with the canoe-shaped radome on its fuselage, which accommodates the phased-array multimode radar. In February 2007, the U.S. Air Force awarded Northrop Grumman Corporation a contract to begin the engineering work required to replace the aging engines on the E-8C Joint STARS aircraft with Pratt and Whitney JT8D-219 engines.

The reengining effort has led to the reconsideration of an issue related to the flying qualities of the aircraft. Specifically, this handling issue was brought about by the size and location of the canoe-shaped radome on the bottom of the fuselage, which can be observed in Fig. 1. The potential for divergent sideslip for an E-8 aircraft was described by Black and Thomas [1] in a 1988 paper that outlined how nominally small changes in aircraft can lead to unintended effects on handling quality, as follows:

> "Any projected side or planform area added ahead of the center of gravity of an aircraft is destabilizing, and must be balanced by the vertical or horizontal tail. In the case of the E-8A, the radome causes an unstable break in directional sideslip angles beyond which the vertical tail stalls. Although this would normally be countered by using opposing rudder to return the aircraft to lower sideslip angles, some other interesting characteristics exist. The limited wind tunnel and flight-test data indicate that for low angle-of-attack, high flap deflection conditions, rudder deflections exist for which the aircraft may diverge in sideslip angle, and opposing rudder may not halt the divergence. The result of such a condition would be a departure from controlled flight, which could have serious consequences."

It is important to note that since the time this description was given in the late 1980s, other nominally minor changes to the E-8C aircraft have taken place. The primary goal of the current investigation was to perform a series of tests on a geometry that very closely matches that of the actual, existent E-8C. This encompassed both wind-tunnel testing carried out at the Air Force Institute of Technology (AFIT), as well as flight tests carried out for the E-8C. These data are needed to provide a baseline for eventual comparisons to a reengined E-8C aircraft.

Within the course of wind-tunnel testing, the flexibility offered by rapid prototyping of aircraft models led to a secondary goal of this research effort. Specifically, one E-8C model was built with winglets, based on the geometry described by Meyer[2] and Flechner [3]. This provided a platform for performing meaningful comparisons to archival data, because Boeing 707 airframes were used to build both the KC-135 aircraft retrofitted in the NASA/U.S. Air Force (USAF) study and Joint STARS fleet. The flight tests performed in the NASA/USAF study showed that the winglets reduced fuel consumption by between 3 and 7%, depending on flight envelope. Also, by virtue of the placement of the winglets on a swept wing, the increased vertical surface area aft of the aircraft center of gravity (CG) led to an increase in the directional stability of the aircraft for the KC-135. This was confirmed through an extensive battery of wind-tunnel tests, which included many combinations of flap, elevator, and aileron settings [2–4].

In addition to the NASA/USAF study, there have been other studies which bolster the idea that winglets reduce the rate of fuel consumption and improve some aspects of aircraft handling qualities. For example, Van Dam, Holmes, and Pitts [5] studied how winglets affected the handling qualities of general aviation aircraft and demonstrated that "[a]irplane climb performance is improved considerably due to winglets and, as a result, the service ceiling of the airplane with winglets will be higher. The maneuverability of the airplane in terms of minimum time to turn 360 deg is upgraded significantly." Improvements in aileron effectiveness due to winglets were also reported in the NASA/USAF study. Chattot [6] likewise documented that optimal winglets increase directional stability even in the presence of viscous effects.

II. Experimental Approach

The model building was performed using drawings of the E-8C provided to researchers at AFIT by the Joint STARS test force. One of the more challenging steps in the research program was converting the 2-D drawing files to a realizable 3-D solid part which could be used to generate a model. This was aided through the use of the software program Magics®, which allowed the importation of a set of approximately 3800 surfaces contained in an IGES file. Despite the use of software tools, considerable time was required to ensure that the model was thoroughly solid by manually stitching surfaces together in some instances. Once the baseline model was made into a

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Fig. 1 Picture of an E-8C Joint STARS aircraft in flight.

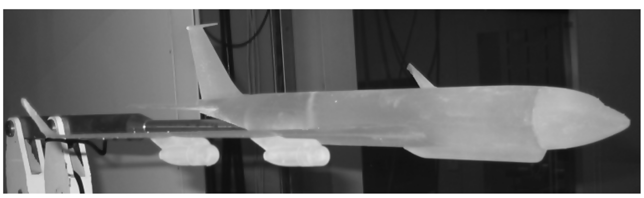

Fig. 2 Photograph of the Model E-8C baseline Joint STARS with radome and straight rudder used in the wind-tunnel tests.

solid and exported to SolidWorks®, subsequent modifications of the model to allow for mounting in the tunnel were, by comparison, straightforward. The E-8C model used in the wind-tunnel study was built of plastic using an Objet Eden® 333 rapid prototype builder. The table of the model limited the single-piece model volume to 13.5 by 13.5 by 10 in., which led to a wingspan of 14.1 in. and mean aerodynamic chord of 2.21 in., which represents a scale-down of 140:1 from the aircraft. This machine can produce very accurate models because it lays down material in 16 μm (0.0006 in.) per pass. Four subsequent models were built using the same approach: 1) with a rudder deflected 25 deg, 2) with the radome removed, 3) with both the radome removed and the rudder deflected, and 4) with winglets. The model with winglets is shown in Fig. 2. Each of the winglets, which were based on the geometry used in the NASA/USAF study, had an area equal to 11.5% of that of the vertical tail.

Two different materials are used for the models: FullCure 720® and VeroBlue® material. Single-piece models removed any uncertainty that would have been present with model assembly. Multiple models were chosen over a single variable model because of the relatively low cost and simplicity of the multimodel approach. A critical scenario to consider from an aircraft stability standpoint included cases with flaps deployed. However, rather than build both changes into the model, for the purposes of this study it was deemed appropriate to first focus on measurements of the effect of the rudder deflection and the combined effects of the radome and the rudder deflection. Each of the models discussed herein used flow-through nacelles in place of the engines. These models are discussed in more detail elsewhere [7].

Tests were conducted in the AFIT low-speed wind tunnel. This tunnel has a 41 in. wide by 33 in. high test section with three-sided optical access and is capable of generating airspeeds up to 145 mph. A Modern Machine & Tool six-component, 0.5-in.-diam, nominally 10 lbf balance (with a range of 10 lbf normal force, 5 lbf axial and side force, and moment limits of 10 in. · lbf) with a manufacturer-specified accuracy to within 0.25% was used for the testing to collect measurements of the loads. Data were acquired at a rate of 100 Hz and averaged over 15 s per data point. All data discussed herein were collected at a nominal airspeed of 80 mph. True air speeds measured with the tunnel differential pressure gauge were used to compute coefficients. Repeatability checks were conducted by fully removing and reinstalling one of the models on a different day. These checks, also conducted at 80 mph, indicated that the measurements for C_n and C_Y were repeatable to within 0.001. The minimum drag coefficient $C_{D,0}$, which typically corresponded to an axial load of around 0.10 lbf, was repeatable to within 0.001, and $C_{L,\max}$ was repeatable to within 0.0005.

Balance interactions were accounted for using a vendor-supplied 6 by 27 interaction matrix. Wind-tunnel wall effects and blockage, both of which were reasonably minor given the size of the model compared to the tunnel cross section, were dealt with using standard approaches described by Barlow et al. [8]. The sting, fitted with the balance, was positioned near the bottom of the model to limit interference with the tail, and the rapid prototype builder enabled this position to be maintained precisely the same for each model, which is particularly critical for moment coefficient measurements. For all results shown herein, moment coefficients were adjusted to the 31% mean aerodynamic chord (MAC) station, which is the farthest aft allowable CG for most of the results presented here because it represents a worst-case scenario for directional stability. Moment coefficients were also computed for the 25% MAC station, which is more commonly used as a reference, to allow for rapid comparison to the literature.

III. Results

The principal reason for this investigation is embodied in the results shown in Fig. 3, which shows a comparison of results acquired during a beta run for two of the models, each of which correspond to data acquired for a zero-sideslip lift coefficient of 0.3. Data for each run were acquired by setting the sideslip angle to a positive value and decreasing β during the run. Both of the models compared in the graph have rudders deflected 25 deg and, thus, they each provide a positive yaw moment coefficient at zero sideslip. The difference in the models is that one E-8C model does not have the canoe-shaped radome. The reduced slope of C_n for negatively varied sideslip angle β graph illustrates that the effect of the radome is indeed to slightly directionally destabilize the aircraft. However, it is notable that the yaw moment coefficient does remain negative for the E-8C as sideslip angle decreases up to negative 30 deg, suggesting that the rudder deflection would provide control authority at large angles of sideslip.

Flight-test data collected by the Joint STARS test force was compared to the E-8C wind-tunnel data using the data presented in Fig. 3. Because of considerations related to the U.S. Department of Defense public release policy, only a limited comparison to the flight tests is described herein. During flight tests, a beta vane was used to determine sideslip angle under a variety of conditions. A variety of flap settings were used during flight testing, but here only the flap-retracted results, which correspond to the geometry used in these wind-tunnel tests, were used for comparison to the wind-tunnel data.

During flight tests it was necessary to maintain trim ($C_n = 0$), and so the rudder was deflected to a series of different angles and its angle

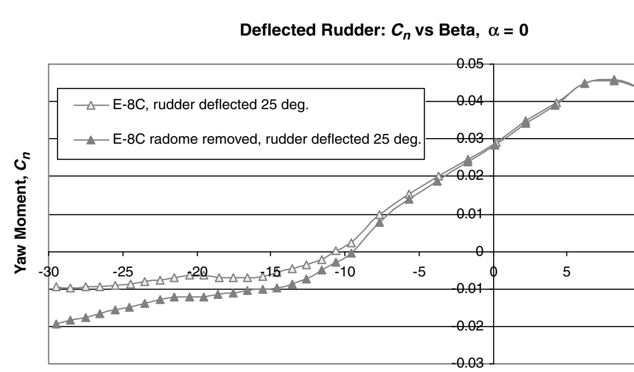

Fig. 3 Wind-tunnel data for the models with the rudder deflected to the right by 25 deg. Data were acquired by starting at positive β and sweeping to $\beta = -30$ deg and is shown here for a CG of 31% MAC. C_L for this α setting was approximately 0.25.

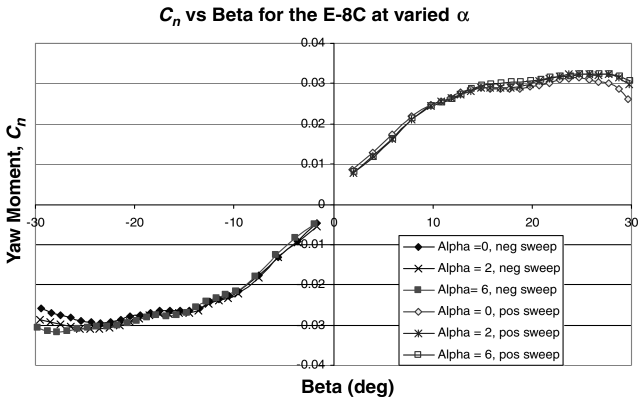

Fig. 4 Yaw moment coefficient plotted as a function of sideslip angle for the model E-8C at different angles of attack.

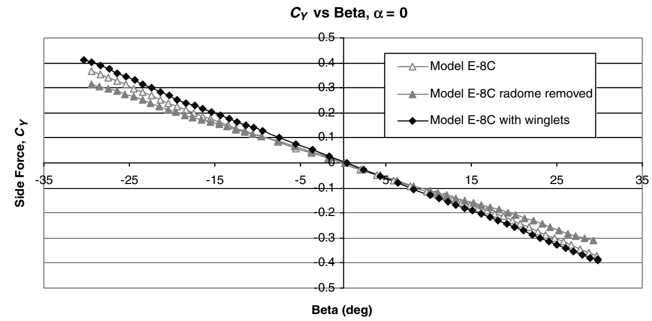

Fig. 5 Side force coefficients for the models indicated.

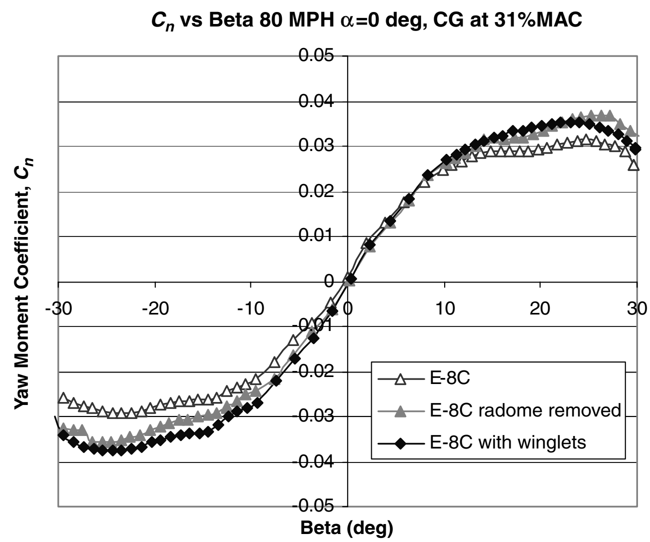

Fig. 6 Yaw moment coefficient as a function of sideslip angle for the four models indicated at $\alpha = 0$ deg ($C_L \approx 0.3$).

was measured along with the sideslip angle. The combination of known rudder deflection angle (δr) and β was used to determine the ratio, $C_{n\text{-}\delta r}/C_{n\text{-}\beta}$. The wind-tunnel test represented in Fig. 3 also provides this information, but only for a singular point at $\beta = 0$ deg. For the wind-tunnel test at $\alpha = 0$ deg, $C_{n\text{-}\delta r}$ is 0.0012, whereas $C_{n\text{-}\beta}$ is -0.0022, yielding a ratio of -0.55. The wind-tunnel data point value was within 1 standard deviation of the mean for the flight-test results conducted for a variety of trim conditions. Considering the differences in Reynolds number and CG position between the flight tests and the wind-tunnel testing, this level of correspondence is reasonable. Notably, a lower magnitude of -0.46 for the value of $C_{n\text{-}\delta r}/C_{n\text{-}\beta}$ was measured in the wind-tunnel tests of the E-8C with the radome removed, due to the increased value of $C_{n\text{-}\beta}$.

To document the influence of angle of attack on the directional stability, data were acquired for the E-8C with the straight rudder at three angles of attack, $\alpha = 0$, 2, and 6 deg, while varying the sideslip angle for the models. Data were acquired for both positive and negative beta sweeps starting with a zero-sideslip angle for an airspeed of 80 mph, corresponding to $Re = 2 \times 10^5$. The data, presented in Fig. 4, illustrate that α has a minor influence in the linear region between ± 10 deg, and that the lowest setting ($\alpha = 0$ deg) yielded the lowest values for C_n at sideslip angles outside this range. Importantly, no particularly unusual trends in the nonlinear region of the curve were discovered.

Although the data given in Figs. 3 and 4 enhance understanding of the effect that the radome has on the directional stability of the E-8C, it is by no means comprehensive. Whereas directional stability could be increased by enlarging the vertical tail, the increased skin friction drag would slightly reduce the range of the aircraft. In the course of our study, winglets of the aforementioned geometry were studied because data suggest that the aircraft range might be extended through the reduction of drag induced by lift.

Side force coefficient data are shown in Fig. 5 for the models E-8C, E-8C with the radome removed, and E-8C with winglets. As one might anticipate, noting that both the radome and the winglets increase vertical area, the side force coefficient increases as vertical area increases. In each instance, the trend is essentially linear between the sideslip angles of -30 and $+30$ deg.

The respective trends present in the yaw moment coefficient data might also be anticipated if one considers the longitudinal placement of the respective vertical surfaces. As can be seen in Fig. 1, the radome is forward of the CG of the aircraft, whereas the winglets on the swept wing are well aft of the aircraft CG. Yaw moment coefficient data is given in Fig. 6 for the $\alpha = 0$ deg case for an airspeed of 80 mph ($Re = 2 \times 10^5$). In each plot, the moment coefficient values were adjusted to the 31% MAC station for each model, as that is the farthest aft allowable CG for the aircraft. Note that the three models correspond to zero rudder deflection. The C_n values corresponding to each model reach a local extrema in the region between 14 and 18 deg of sideslip. One indicator is the minimum value attained for C_n for this experiment for negative sideslip angle. Models E-8C, E-8C with the radome removed, and E-8C with winglets reached a minimum value of C_n of 0.029, 0.036, and 0.038, respectively, with each value accurate to approximately ± 0.001. This suggests that for the condition tested the vertical surface addition via the winglets was sufficient to offset the vertical surface of the radome. If this trend is broadly applicable to other conditions (i.e., different angles of attack, flaps and landing gear deployed, etc.), winglets could be used to counter the destabilizing effect of the radome.

A second metric for identifying the trends in directional stability is the slope $C_{n\text{-}\beta}$ in the linear portion of the curve corresponding to low sideslip angles. These data were collected for the 0 deg case shown in Fig. 6 as well as for the 2 and 6 deg cases, which represent a C_L range from approximately 0.2 to 0.8. The value of $C_{n\text{-}\beta}$ was computed using a least-squares fit for the data ranging from $\beta = -10$ to $+10$ deg.$C_{n\text{-}\beta}$ was found to be 0.0022 ± 0.0001 for the E-8C and was 0.0027 ± 0.0002 for both the E-8C with the radome removed and the E-8C with winglets. These data are given for the 25% MAC to provide a ready comparison to the literature. In NASA TP 1330, Flechner [3] reported that $C_{n\text{-}\beta}$ increased by approximately 0.0004 for winglets added to a KC-135. This compares to an increase of about 0.0005 for $C_L = 0.3$ in our results.

The correspondence of our data is important because these archival NASA reports contain directional stability data for a myriad of conditions including a variety of flap settings. By and large, this literature indicates that the improved directional stability due to winglets generally persisted for the KC-135 for flap-deflected cases, as well as for a wide variety of combinations of control surface settings.

Lift and drag was also measured during the course of the wind-tunnel testing for the three models without rudder deflection, and a drag polar is given in Fig. 7. The drag coefficient for the E-8C with the radome removed model consistently yielded the lowest value for

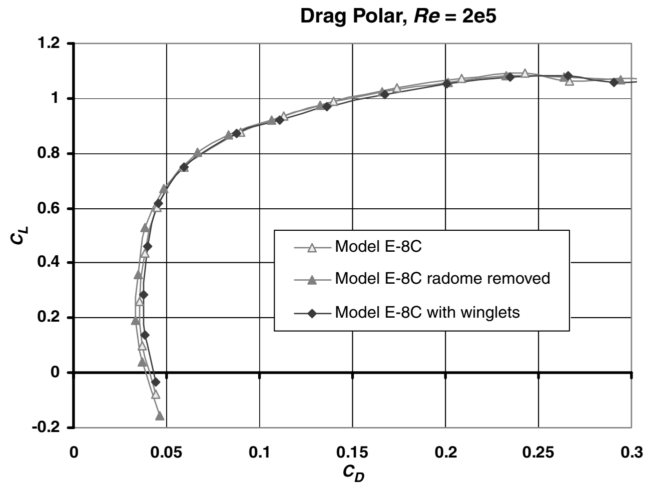

Fig. 7 Drag polar for the three models without rudder deflection.

minimum drag coefficient, whereas the E-8C with winglets model increased the minimum drag coefficient over that of the baseline E-8C. This is in line with expectations that both the radome and the increased surface area of the winglets increase drag at zero lift. At angles of attack ranging from about 5 to 8 deg, the drag coefficient for the E-8C with winglets model is virtually the same as that of the E-8C. This is consistent with the idea that winglets reduce the induced drag. Given the Reynolds number of the testing environment ($Re = 2 \times 10^5$), it is not surprising that the observed differences in the lift-to-drag ratio of the models are small. Because scaling up the model reduces the magnitude of the skin friction drag coefficient while leaving unchanged the induced drag coefficient, one might anticipate that the net effect of the winglets on the full-scale model would be improved beyond the amount represented here.

When one considers the Reynolds number effects, it should be noted that the directional stability is mainly influenced by side force on the winglets, which is due to the local lift per unit span of the (principally vertical) winglet, an inviscid phenomena. Thus, it is not surprising that our results for directional stability closely correspond to the full-scale results given in [3]. By contrast, any improvements of induced drag are at least partially offset by the increased skin friction drag of the winglets, which is a viscous effect strongly influenced by the Reynolds number.

IV. Conclusions

Wind-tunnel measurements conducted on a variety of E-8C configurations were collected and compared to flight-test data. The primary goal of this study is to collect baseline data relating to the directional stability characteristics of the actual E-8C geometry. The wind-tunnel tests used precise geometrically 140:1 scaled-down models of the E-8C and were constructed using a rapid prototype builder. The series of wind-tunnel tests quantified the extent to which the radome directionally destabilizes the clean configuration of the aircraft. As has been documented in the literature, the radome does lead to a decrease in the slope of the linear portion of the $C_{n\text{-}\beta}$ curve. However, the radome did not appear to introduce any unusual nonlinear effects at larger sideslip angles.

Although the wind-tunnel tests revealed that the slope of the $C_{n\text{-}\beta}$ curve reverses near a sideslip angle of 16 deg for the 31% MAC CG position for a reference angle of attack of zero degrees ($C_L = 0.3$), the moment itself remains restoring for increased sideslip angle magnitude. The low angle-of-attack case was found to be the worst-case scenario for directional stability for the clean aircraft configuration at the conditions tested. Models constructed with the rudder deflected provided the means to make limited comparisons to flight-test data. The combined effects of sideslip angle and rudder deflection angle on C_n were analyzed and, based on this analysis, the wind-tunnel results corresponded well with flight-test data collected at trim conditions.

A portion of the wind-tunnel study was devoted to exploring the effects of winglets on the aircraft. Care was taken to build winglets of the same geometry as that used in the NASA/USAF study for the KC-135, which is based on a Boeing 707 air frame like the E-8C. The testing revealed that the winglets increased the directional stability of the aircraft, and that this increase is sufficient to offset the destabilizing effect of the radome. The archival literature indicates that the improved directional stability due to winglets generally persisted for the KC-135 for a wide variety of aircraft configurations. Furthermore, a significant improvement in fuel economy, verified in flight tests of the KC-135, was measured when winglets were installed as part of that study [2].

The body of evidence thus suggests that an increase in directional stability for the E-8C may be obtained by an investment in winglets, which in turn would lead to an appreciable reduction in fuel costs. Therefore, it is recommended that a thorough investigation of the structural feasibility and payback period for a winglet retrofit be given due consideration, perhaps in conjunction with the proposed reengining of the E-8C.

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