Mathematical and Computer Modelling 49 (2009) 1359–1371

Contents lists available at ScienceDirect

Mathematical and Computer Modelling

journal homepage: www.elsevier.com/locate/mcm

Applying Taguchi's off-line quality control method and ANOVA on the maneuverability of the F-5E intake

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ARTICLE INFO

Article history:
Received 23 November 2007
Received in revised form 26 November 2008
Accepted 8 January 2009

Keywords:
F-5E
Engine intake
Taguchi's robust design
Flow distortion
Maneuvers

ABSTRACT

Air quality leading up to the compressor face of a fighter aircraft determines the engine performance considerably. A deficiency in the quality could lead to flutter or stall in the engines. In this study, two statistical methods; the Taguchi Method (TM) and the Analysis of Variance (ANOVA) are used to evaluate airflow quality through the intake via fighter aircraft maneuvers. The three factors associated directly with aircraft maneuverability are the Mach number (M), Angles of Incident (α) and Sideslip (β). Desirable air quality can be described as having high pressure recoveries as well as low distortion at the Aerodynamic Interface Plane (AIP). The intake studied is the port side F-5E duct. Results show that an increase in the Mach number affects the streamwise diffusion of the fluid more than the changing the angles of attack and sideslip, resulting in lower pressure recovery. The secondary flow formation in the streamwise direction is unable to dissipate and increases in strength with increasing Mach number. The curvature in the z-axis is more pronounced than that existing in the x-axis, leading to the formation of more adverse pressure gradients forming and hence greater secondary flow strength. This results in a more distorted flow leading to the AIP. This observation is in tandem with the values of the DC (60) readings obtained. The F-5E's Taguchi's Method results show that Mach number had the greatest effect on pressure recovery, and AOA affected distortion most considerably. Results from ANOVA show that Factors A, B and C and Interactions AC and BC affect the distortion of airflow. However, Factor B or the angle of attack affects this distortion most significantly.

1. Introduction

The use of Advanced Statistical Techniques (AST) such as the Design of Experiment (DoE) and the Taguchi Method (TM) have been fairly common in the industrial engineering fraternity. DoE is a powerful tool for process optimization and studying the product and process behavior. It is used for discovering the set of process variables that are influential on the process output and the levels at which these variables should be kept to optimize process performance. TM, on the other hand, are used for maximizing product and process robustness by reducing variation due to undesirable external disturbances which cannot be controlled during actually production conditions in Montgomery [1].

Amongst the applications of AST in manufacturing organizations are the injection molding, welding and chemical processes. In these processes, the main purpose of employing these techniques is to tackle process quality problems in real-life situations. However, not all AST implications are used in the industrial engineering field.

The helicopter experiments conducted by Antony and Antony [2] Antony and Antony [3] identified factors which affect the time of flight and to determine the optimal factor levels which will maximize the time of flight. A two-level (a high

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0895-7177/$ – see front matter
doi:10.1016/j.mcm.2009.01.006

Table 1
The k-ε modeling constants used.

Model	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	C_{μ}	σ_k	σ_{ε}
k-ε	1.44	1.92	0.09	1.0	1.3

or low value) fractional factorial study with 16 experimental runs is selected. The advantage of a factorial design is that it allows the independent estimate of the main factor effects without the need of going through the maximum number of two-level factorial runs. The effects of the interactions of factors are also studied. Analysis of Variance (ANOVA) is carried out to identify the significant and main interaction effects in Antony and Antony [2]. TM was also carried out on the paper helicopter experiment; time including uncontrollable factors called noise in Antony and Antony [3]. Signal-to-noise (SNR) calculations are conducted using the larger-the-better quality characteristics, as the yield measured is actually the flight time.

Other recent studies include the applications of statistical analysis in identifying tumors by Ng and Ng [4]. ANOVA and TM are conducted on these 3 two-level factorial designs. As with the previous studies, the aim is to maximize the surface potential from the tumor size and location relative to the tumor conductivity. Again this uses the larger-the-better concept that was implemented in the previous study.

Perhaps a more interesting design experiment involved the optimizing of the CFD solver itself in Anderson et al. [5]. As of the previous two works, numerical methods were used to obtain the results needed. This study involved TM to identify trends in the solver's performance. The relative effects of turbulent model, Reynolds number, angle of attack and wall spacing (y^+) (factors) determines the level of error in the lift and drag coefficients (yield/result). Again, two-level factors are used in this study. A response table of the results was also set up. The results gathered help to pinpoint flow regions where non-linear interactive effects may be most important. In the presence of noise, TM can highlight solver parameters and flow regimes that may be insensitive to changes in the calculation environment, making them good candidates for off-design calculations. Other group of factors in CFD experiments may yield further conclusions about improving solver performance or behavior over wide regions.

The study of the role of DoE in managing inlet air flow had also been conducted in Anderson et al. [5]. The goal of the study was to maintain optimal inlet performance over a range of mission variables and to explore the use of AST in understanding the management of inlet air flow. The M2129 inlet S-duct was chosen as the geometry of study. The factor variables were the number of vane effector units, height, length, inlet throat Mach number and angle of incident. Optimum flow is defined in three mission strategies, namely (1) Maximum Performance, (2) Maximum Engine Stability and (3) Maximum High Cycle Fatigue (HCF) Life Expectancy. The Maximum Performance mission minimized the inlet total pressure losses; the Maximum Engine Stability mission minimized the engine face distortion while the Maximum (HCF) Life Expectancy mission minimized the mean of the first five Fourier harmonic amplitudes.

Numerical parametric studies at the compressor region using TM have also been conducted by Wu et al. [6] and Ng et al. [7]. In both studies, 3 three-level factors (each factor is having three different levels) were used to measure flow with the least distortion at the compressor face. This results in an L_{27} (3^3) orthogonal array design similar to the numerical experiment that will be carried out. Using the Taguchi off-line quality control method, the parameters; namely inlet x-axis distorted velocity coefficient, incidence angle and drag-to-lift coefficient; are ranked according to the degree of influence in distortion. Further case studies were also conducted by varying only one factor with multiple levels.

The study to maintain optimal inlet performance over a range of mission variables and to explore the use of AST in understanding the management of inlet air flow was conducted on the M2129 inlet S-duct. The factor variables were the number of vane effector units, height, length, inlet throat Mach number and angle of incidence. Optimum flow is defined in three mission strategies, namely (1) Maximum Performance, (2) Maximum Engine Stability and (3) Maximum High Cycle Fatigue (HCF) Life Expectancy. The Maximum Performance mission minimized the inlet total pressure losses; the Maximum Engine Stability mission minimized the engine face distortion while the Maximum (HCF) Life Expectancy mission minimized the mean of the first five Fourier harmonic amplitudes.

The focus of the current investigation is to study the effects of airflow prior to the entrance to the compressor face, as reported by Ng and Liu [8]. The diffuser, or the intake, plays a pivotal role in supplying high quality air into the compressor face. By studying the effects of varying Mach number, angles of attack and sideslip, the compromise in air quality during an aircraft maneuver can be studied using both TM and ANOVA.

2. Numerical analysis

The present simulations have been performed using COMSOL [9,10] based on the finite element approach. The fully compressible model is expressed by coupling the continuity and momentum equations in the k-ε turbulence mode together with the energy equation obtained in the conduction and convection modes, as suggested by Smith [11]. The model is used on the circular S-duct, F-5E and F-16 intake. The k-ε physics settings were modeled using the General form. The modeling constants are included in Table 1.