Predict Aircraft Engine Compressor Stall

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Project Background

This is a simplified form of our Systems Engineering thesis, "A Method To Predict Compressor Stall In The TF34-100 Turbofan Engine Utilizing Real-Time Performance Data".

Question to Answer: Is there an engine compressor stall fault on next flight based on current flight engine data?

VG (Variable Geometry) is calculated from 3 engine sensors (T2C, NG and IGV). Then AutoRigression Integrated Moving Average (ARIMA) method is used for time series modeling. With sampled engine training dataset, a Linear Regression Model (LRM) is fitted to associat the predictors (ARIMA coefficients) to the outcome. Therefore, this LRM can be used to predict the chance of Engine Compressor Stall on next flight.

This **ARIMA-LRM method** will be explained mathematically on next pages.

Original Thesis Cover

ARIMA-LRM Method (1)

Engine sensor data is a Time Series data.

$$X_t = f(T2C, NG, IGV)$$

$$\begin{aligned} X_t &= \delta + AR_1 X_{t-1} + AR_2 X_{t-2} + ... + AR_p X_{t-p} \\ &+ A_t + MA_1 A_{t-1} + MA_2 A_{t-2} + ... + MA_q A_{t-q} \end{aligned}$$

Where X_t is the VG value at the time t, $AR_i (i = 1, 2, ..., p)$ is the AutoRegression (AR) coefficient, and $MA_j, (j = 1, 2, ..., q)$ is the Moving Average (MA) coefficient.

This model is denoted as $arima(p, 0, q)$.

ARIMA-LRM Method (2)

In the engine training dataset which contains N engines, M with *compressor stall* thus outcome $y_i = 1$; for others clear of faults $y_i = 0$, where $(i = 1, 2, ..., n)$.

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \\ y_{m+1} \\ \vdots \\ y_n \end{pmatrix} \sim \begin{pmatrix} AR_{1_1} & AR_{2_1} & \dots & AR_{p_1} & MA_{1_1} & MA_{2_1} & \dots & MA_{q_1} \\ AR_{1_2} & AR_{2_2} & \dots & AR_{p_2} & MA_{1_2} & MA_{2_2} & \dots & MA_{q_2} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ AR_{1_n} & AR_{2_n} & \dots & AR_{p_n} & MA_{1_n} & MA_{2_n} & \dots & MA_{q_n} \end{pmatrix}$$

ARIMA-LRM Method (3)

Therefore, a Linear Regression Model can be fitted as

$$p_{ecs} = \beta_0 + \sum_{i=1}^{p} \beta_i * AR_i + \sum_{j=1}^{q} \beta_{j+p} * MA_j + \epsilon$$

Obtained ARIMA-LRM Coefficients

From original samples in our thesis, LRM coefficients is obtained

$$\hat{p}_{ecs} = \hat{\beta}_0 + \sum_{i=1}^{p} \hat{\beta}_i * AR_i + \sum_{j=1}^{q} \hat{\beta}_{j+p} * MA_j$$

$\hat{\beta}_0 = 0.240$ | Intercept Estimate

$\hat{\beta}_1 = 5.348, \hat{\beta}_2 = 5.967, \hat{\beta}_3 = 9.755, \hat{\beta}_4 = -2.721$ $\hat{\beta}_5 = 4.616, \hat{\beta}_6 = 5.575, \hat{\beta}_7 = -0.447, \hat{\beta}_8 = 2.163$ $\hat{\beta}_9 = 2.471, \hat{\beta}_{10} = 13.484, \hat{\beta}_{11} = 0.792, \hat{\beta}_{12} = 11.931$ | $AR_1 \sim AR_{12}$ Estimates

$\hat{\beta}_{13} = 5.831, \hat{\beta}_{14} = -2.100, \hat{\beta}_{15} = 4.201, \hat{\beta}_{16} = -5.785$ | $MA_1 \sim MA_4$ Estimates

Where $arima(12, 0, 4)$ model has been used.

Variable Geometry Calculation Formula

Calculate NGC first

$$NGC = \frac{NG}{\sqrt{\frac{T2C+273.15}{288.15}}}$$

- IF $T2C < 23.8°C$

$$VG = IGV + 0.862 * NGC - 112.470$$

- IF $23.8°C \leq T2C \leq 37.7°C$

$$VG = IGV + (0.862 * NGC - 112.5) + \frac{(1.005 * NGC - 71.408) * (T2C - 23.889)}{13.9}$$

- IF $37.7°C < T2C$

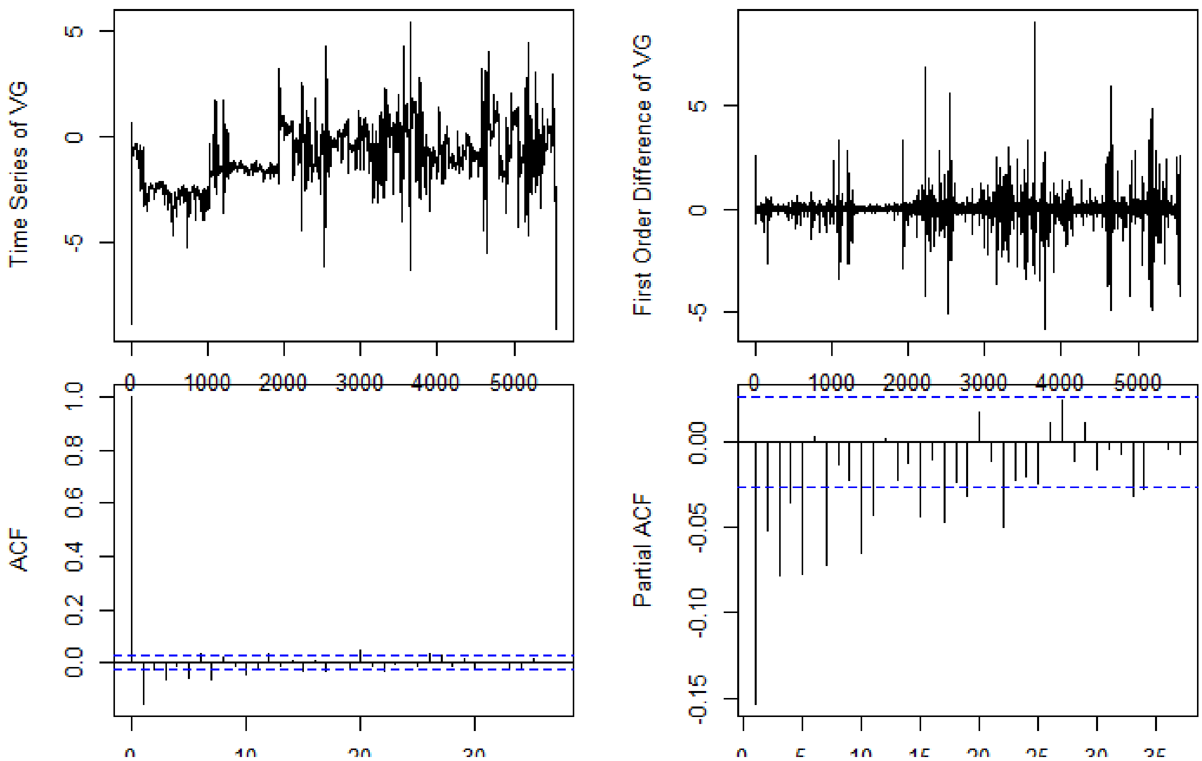
$$VG = IGV + 1.439 * NGC - 150.898$$

Process in shinyapps.io Project

- Upload an example file which has four columns: GPS Time, T2C, NG and IGV
- Calculate VG values by row
- Plot VG_t; $diff(VG_t)$; $acf(diff(VG_t))$ and $pacf(diff(VG_t))$
- Calculate $\hat{p}_{ECS}$
  - IF $\hat{p}_{ecs} > 0.5$, "**WARNING: COMPRESSOR STALL IN NEXT FLIGHT**"
  - IF $\hat{p}_{ecs} < 0.5$, "**CLEAR: NORMAL CAUTION APPLY IN NEXT FLIGHT**"

Load, Calculate and Plot Data

```r
par(mar=c(1.5,5,.1,1));par(mfrow=c(2, 2))
x <- read.csv("810962-1624-LEFT-example-rted.csv"); VG <- ts(vg_cal(x)); xd <- diff(VG)
plot(VG,ylab="Time Series of VG");plot(xd,ylab="First Order Difference of VG");acf(xd); pacf(xd)
```



Calculate $arima(p, 0, q)$ Coefficients

Where $arima(12, 0, 4)$ model has been used.

```r
arimaFit <- arima(xd,order=c(12,0,4),optim.method="Nelder-Mead")
```

Coef_AR1	Coef_AR2	Coef_AR3	Coef_AR4	Coef_AR5	Coef_AR6
-6.99633e-02	5.00714e-03	-4.27208e-03	-1.52865e-02	-9.3977e-03	-1.06113e-02

Coef_AR7	Coef_AR8	Coef_AR9	Coef_AR10	Coef_AR11	Coef_AR12
9.70626e-03	2.69551e-02	1.4019e-03	7.45334e-03	5.45178e-03	1.39239e-02

Coef_MA1	Coef_MA2	Coef_MA3	Coef_MA4
-3.55007e-03	2.40141e-02	-3.27156e-03	-7.56296e-04

Predict Engine Compressor Stall

```
Coef_training <- c(0.240, 5.348, 5.967, 9.755, -2.721, 4.616, 5.575, -0.447, 2.163,
                   2.471, 13.484, 0.792, 11.931, 5.831, -2.100, 4.201, -5.785)
p <- Coef_training[1]
for (i in 1:16) {
  p <- p + as.numeric(Coef_training[i + 1]) * as.numeric(tab_coef["coef_calculated", i])
}
if ((p <- format(p, digits=2)) > 0.5) {
  cat("**WARNING: COMPRESSOR STALL IN NEXT FLIGHT  **","($\\hat p_{ecs}=",p,"$)",sep="")
} else {
  cat("**CLEAR: NORMAL CAUTION APPLY IN NEXT FLIGHT  **","($\\hat p_{ecs}=",p,"$)",sep="")
}
```

CLEAR: NORMAL CAUTION APPLY IN NEXT FLIGHT ($\hat p_{ecs} = 0.041$)