Geometric, Stability, and Landing Gear Analysis of the Boeing 777-9 (777X)

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This study presents a geometric reconstruction and stability analysis of the Boeing 777-9 aircraft in accordance with AAE 411 project requirements. A simplified three-dimensional model was developed with a defined datum plane to support aerodynamic and stability calculations. Wing planform geometry, mean aerodynamic chord, and spanwise chord distribution were derived using manufacturer data. Center of gravity locations were calculated for multiple loading configurations and evaluated relative to forward and aft limits. USAF DATCOM was used to determine longitudinal and lateral stability derivatives at multiple flight conditions. Phugoid characteristics and landing gear load distributions were also computed. Results indicate positive static stability within the allowable CG envelope.

I. Nomenclature

b = Wingspan
b_t = Horizontal tail span
$c(y)$ = Wing chord spanwise distribution
$c_i(y)$ = Wing chord distribution of trapezoidal section i
$c_{0,i}$ = Wing inboard chord of trapezoidal section i
$c_{1,i}$ = Wing outboard chord of trapezoidal section i
$\bar{\bar{c}}$ = Wing mean aerodynamic chord
$\bar{\bar{c}}_i$ = Wing mean aerodynamic chord of trapezoidal section i
$\bar{\bar{c}}_t$ = Horizontal Tail mean aerodynamic chord
$c_t(y)$ = Horizontal Tail chord distribution
L = Landing gear wheelbase
R_{NG} = Vertical reaction force at nose gear
R_{MG} = Total vertical reaction force at main gear
S_{ref} = Wing reference area
S_i = Planform area of trapezoidal wing section i
S_t = Total horizontal tail reference area
S_{inside} = Wing planform area inside fuselage
S_{wet} = Wet wing planform area
x_{cg} = Longitudinal center of gravity location, referenced from aircraft nose datum

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$x_{cg,aft}$ = Aft limit center of gravity
x_{np} = Neutral point
SM = Static Margin
$x_{cg,fwd}$ = Forward limit center of gravity
x_{NG} = Longitudinal location of nose landing gear contact point, referenced from aircraft nose datum
x_{MG} = Longitudinal location of main landing gear contact point, referenced from aircraft nose datum
$x_{LE}(y)$ = Leading-edge longitudinal coordinate as a function of spanwise position, with respect to datum
$x_{TE}(y)$ = Trailing-edge longitudinal coordinate as a function of spanwise position, with respect to datum
x_{maxLE} = Leading-edge longitudinal coordinate of the wing MAC
x_{ac} = Quarter-chord aerodynamic center location of the wing
y = Spanwise coordinate measured from centerline
y_{ac} = Spanwise location of wing mean aerodynamic chord
y_{fuse} = Fuselage half-width at wing intersection
λ_i = Taper ratio of trapezoidal wing section
λ_t = Taper ratio of horizontal tail
x_{cg} = longitudinal center of gravity
z_{cg} = vertical center of gravity
x_{np} = *neutral point location*
W = Aircraft weight
W_{OEW} = Operating Empty Weight
W_{PL} = Payload Weight
W_F = Fuel Weight
N_M = Main Landing Gear Load
N_N = Nose Landing Gear Load
n_{main} = Number of main gear tires
n_{nose} = Number of nose gear tires
$F_{main,\ tire}$ = Load per main gear tire
$F_{nose,\ tire}$ = Load per nose gear tire

II. Introduction

The Boeing 777-9, the largest member of the 777X family, was selected for analysis due to the availability of technical specifications and its relevance as a modern long-range transport aircraft. The objective of this study is to recreate the aircraft geometry on a digital platform and perform aerodynamic, stability, and landing gear analyses consistent with class methodology.

A simplified 3-D model was created with an explicitly defined datum plane serving as the reference for all dimensional and CG measurements. The analysis includes wing geometry reconstruction, CG envelope evaluation, stability derivative estimation using DATCOM, phugoid characterization, and landing gear load distribution analysis.

III. Geometric Reconstruction and Aerodynamic Parameters

A. Wing Planform Reconstruction

The Boeing 777-9 wing geometry was reconstructed using manufacturer dimensional data and digitized three-view drawings. Leading-edge and trailing-edge coordinates were extracted at each planform break (kink). The half-span reference stations are:

$$y_0 = 0m, y_{kink0} = 12.0m, y_{kinkt} = 32.425\ m, y_{tip} = \frac{b}{2} = 35.88m$$

The corresponding leading- and trailing-edge x-coordinates relative to the datum were determined from linear fits to the digitized geometry:

$$x_{LE}(y_0) = 25.0\ m,\ x_{LE}(y_{kink0}) = 31.42\ m, x_{LE}(y_{kinkt}) = 43.37\ m, x_{LE}(y_{tip}) = 46.83\ m$$

$$x_{TE}(y_0) = 39.5\ m,\ x_{TE}(y_{kink0}) = 39.90\ m, x_{TE}(y_{kinkt}) = 45.86\ m, x_{TE}(y_{tip}) = 48.01\ m$$

The chord at each boundary was then computed as:

$$c(y) = x_{TE}(y) - x_{LE}(y)$$

Resulting in:

$$c_0 = 13.0\ m, c_{kink0} = 8.48\ m, c_{kinkt} = 2.138\ m\ c_t = 0.627\ m$$

1. Spanwise Chord Distribution

For each trapezoidal section *i*, the chord distribution was assumed linear between its inboard and outboard boundaries:

$$c_{i(y)} = c_{0,i} + \left(\frac{c_{1,i} - c_{0,i}}{y_{1,i} - y_{0,i}}\right)(y - y_{0,i})$$

Where: $c_{0,i} =$ inboard chord of section *i, and* $c_{1,i}$ =outboard chord of section *i.* Inserting each planforms respective values into the chord distribution equations, we derive the following chord length equations for $c_1(y)$, $c_2(y)$, and $c_3(y)$:

$$c_1(y) = 14.5 - 0.502y$$

$$c_2(y) = 8.49 - 0.293(y - 12)$$

$$c_3(y) = 2.49 - 382(y - 32.425)$$

Relating each section's spanwise chord distribution to the overall wing we can derive the following spanwise chord distribution for the entire wing.

$$\boxed{c(y) = \begin{cases} c_1(y) = 14.5 - 0.502y, & y_0 \le y \le y_{kink0} \\ c_2(y) = 8.49 - 0.293(y - 12), & y_{kink0} < y \le y_{kinkt} \\ c_3(y) = 2.49 - 382(y - 32.425) & y_{kinkt} < y \le y_{tip} \end{cases}}$$

2. Wing Reference Area S_{ref}

The wing reference area was calculated through the integration of the chord distribution with respect to the piecewise function, where the integral of each chord function represents the sections respective area S_i:

$$S_{ref} = 2\left[\int_{y_0}^{y_{kink0}} c_1(y)\,dy + \int_{y_{kink0}}^{y_{kinkt}} c_2(y)\,dy + \int_{y_{kinkt}}^{y_{tip}} c_3(y)\,dy\right]$$

Evaluating the integrals and solving we find the half area of each section, and the total wing reference area:

$$\int_{y_0}^{y_{kink0}} c_1(y)\,dy = 137.88\,m^2$$

$$\int_{y_{kink0}}^{y_{kinkt}} c_2(y)\,dy = 112.03\,m^2$$

$$\int_{y_{kink0}}^{y_{tip}} c_3(y)\,dy = 6.32\,m^2$$

$$\boxed{S_{ref} = 512.47\,m^2}$$

This value includes the portion of the wing inside the fuselage, consistent with reference area definitions.

3. Wing Wet Surface Area

Because a portion of the wing lies inside the fuselage, that area does not contribute to the aerodynamic wetted surface. The fuselage half-width at the wing intersection was defined as $y_{fuse} = 3.1\,m$. The embedded planform area was computed as:

$$S_{half,inside} = \int_0^{y_{fuse}} c(y)\,dy$$

$$S_{inside} = 2S_{half,inside} = 85.08\,m^2$$

The wet (exposed) wing planform area was thenL

$$S_{wet} = S_{ref} - S_{inside}$$

$$\boxed{S_{wet} = 427.39\,m^2}$$

4. Mean Aerodynamic Chord $\bar{\bar{c}}$

Because the wing consists of multiple trapezoidal sections with different taper ratios, a single trapezoidal MAC formula cannot be applied globally. Instead, an area-weighted method was used. For each trapezoidal section, the taper ratio is defined as $\lambda_i = \frac{c_{1,i}}{c_{0,i}}$. The MAC of each panel was calculated individually using the trapezoidal distribution expression:

$$\bar{\bar{c}}_i = \frac{2}{3} c_{0,i} \frac{1 + \lambda_i + \lambda_i^2}{1 + \lambda_i}$$

The overall wing MAC was obtained using area weighting:

$$\bar{\bar{c}} = \frac{\sum_{i=1}^{3} \bar{\bar{c}}_i * S_i}{\sum_{i=1}^{3} S_i}$$

Applying this method we find:

$$\boxed{\bar{\bar{c}} = 9.0\,m}$$

Similarly, the spanwise MAC location was determined using the lambda-based expression for each trapezoidal section:

$$y_{ac,i} = y_{0,i} + (y_{1,i} - y_{0,i})\frac{1+2\lambda_i}{3(1+\lambda_i)}$$

The global spanwise MAC location was computed using area weighting:

$$y_{ac} = \frac{\sum_{i=1}^{3} y_{ac,i} * S_i}{\sum_{i=1}^{3} S_i}$$

Applying this method we find:

$$\boxed{y_{ac} = 12.683\, m}$$

5. *Longitudinal Location of MAC*

Sweep effects were incorporated through the spanwise variation of the leading edge. For each section the leading edge location of the MAC was defined as $x_{macLE,i}$:

$$x_{macLE,i} = x_{LE,0,i} + (x_{LE,1,i} - x_{LE,0,i})\frac{1+2\lambda_i}{3(1+\lambda_i)}$$

The global leading-edge MAC location was:

$$x_{macLE} = \frac{\sum_{i=1}^{3} x_{macLE,i} * S_i}{\sum_{i=1}^{3} S_i}$$

The quarter-chord aerodynamic center of the wing as then determined as:

$$x_{ac} = x_{macLE} + 0.25\bar{\bar{c}}$$

$$\boxed{x_{ac} = 32.263\, m}$$

6. *Horizontal Tail Area S_t and Horizontal Tail $\bar{\bar{c}}_t$*

The horizontal tail planform was modeled as a single trapezoidal surface using half-span symmetry. Geometric data were obtained from digitized three-view drawings and manufacturer dimensions. The half-span of the horizontal tail was defined as $y_{t0} = 0\, m$, and $y_{ttip} = 12.28\, m$. leading-edge and trailing-edge longitudinal coordinates were extracted relative to the same datum used for the main wing: $x_{LE,t0} = 64.1\, m$, $x_{LE,ttip} = 73.67\, m$, $x_{TE,t0} = 71.7\, m$, and $x_{TE,ttip} = 76.85\, m$. The chord length at each spanwise boundary was computed as, $c_{t0} = 7.6\, m$ and $c_{ttip} = 2.172\, m$. Applying these parameters to the trapezoidal chord distribution equation, we find $c_t(y)$:

$$\boxed{c_t(y) = 7.6 - 0.422y}$$

The half-tail area was computed by integrating the chord distribution over the half-span. The total horizontal tail reference area was then obtained by symmetry to both sides.

$$S_{t,half} = \int_0^{y_{ttip}} c_t(y)\, dy$$

$$S_t = 2S_{t,half}$$

$$\boxed{S_t = 120\, m^2}$$

Because the tail planform is trapezoidal with linear chord variation, the mean aerodynamic chord was computed using the closed-form trapezoidal expression:

$$\lambda_t = \frac{c_{ttip}}{c_{t0}}$$

$$\overline{\overline{c_t}} = \frac{2}{3}c_{t0}\frac{1+\lambda_t+\lambda_t^2}{1+\lambda_t}$$

$$\boxed{\overline{c_t} = 5.39\ m^2}$$

B. Center of Gravity Calculations

1. *Aircraft Design Weights*

The primary design weights for the Boeing 777-9 were obtained from the Boeing 777-9 Airplane Characteristics for Airport Planning document [1]. The maximum design takeoff weight (MTOW) is 351,534 kg, the maximum design landing weight (MLW) is 266,258 kg, and the maximum design zero fuel weight (MZFW) is 254,918 kg. The maximum design taxi weight is 352,441 kg. In addition, the maximum usable fuel capacity is 197,228 kg. These certified weight limits define the loading conditions used in the subsequent center of gravity analysis.

All longitudinal positions are referenced to the aircraft nose datum unless otherwise specified.

2. *c.g. locations for each weight and check it out with forward and aft limits.*

Formula for center of gravity:

$$x_{cg} = \frac{\sum_{i=1}^{n} W_i x_i}{\sum_{i=1}^{n} W_i}$$

Assumptions (simplified mass distribution)

Because Boeing airport planning data provide design weights but do not publish weight-and-balance station data for specific loading cases, a simplified 3-lumped-mass model is used (all x locations referenced to the same aircraft nose datum used for x_NG and x_MG).

The operating empty weight (OEW) was estimated using published 777-9 technical data indicating an OEW of approximately 400,000 lb (≈181,400 kg) [X]. This value is consistent with 777-9 structural weight fractions and is within 1% of the assumed 0.72·MZFW approximation used in the simplified mass model.

- Operating Empty Weight located at x_OEW=35.865 m (midpoint of CG envelope)
- Payload located at x_PL=36.10
- Fuel located at x_F=35.60
- Operating Empty Weight magnitude assumed as a fraction of MZFW:
  W_OEW=0.72 * W_MZFW

Given Boeing design weights (Model 777-9)

W_MTOW=351,534 kg ; W_MLW=266,258 kg ; W_MZFW=254,918 kg; W_fuel,max = 197,228 kg

Loading cases (weights used)

1) Empty (no payload, min fuel):

W=W_OEW

2) Max takeoff (MTOW):

W_PL=W_MZFW-W_OEW, W_F = W_MTOW-W_MZFW

3) Max fuel (no payload ferry, constrained by MTOW):

W_PL=0, W_F=W_MTOW-W_OEW

4) Landing (max payload, min fuel at MLW):

W_PL=W_MZFW-W_OEW, W_F=W_MLW-W_MZFW

Computed longitudinal x_cg for each configuration

- Empty (OEW): x_cg=35.87
- MTOW: x_cg=35.84
- Max fuel (no payload): x_cg=35.74 m
- Landing (max payload, min fuel): x_cg=35.92 m

Check against forward/aft CG limits

Using the subsequently determined longitudinal CG limits:

$$\boxed{x_{cg,fwd} = 35.37\ m} \qquad \boxed{x_{cg,aft} = 36.36\ m}$$

Each loading case satisfies:

$$\boxed{x_{cg,aft} < x_{cg} < x_{cg,fwd}}$$

3. Max forward and aft cg x-locations in m. and in xcg/$\bar{c}$.

Formula for wheel base:

$$L = x_{MG} - x_{NG}$$

Formula for longitudinal c.g. location from gear reactions:

$$x_{cg} = x_{NG} + (\frac{R_{MG}}{W})\,\mathrm{L}$$

with

$$R_{MG} = W - R_{MG}$$

General Formula for the forward center of gravity limit:

$$x_{cg,fwd} = x_{NG} + 29.47\ m$$

We want the distance in the aft direction, with respect to the nose tip. Therefore:

$$\boxed{x_{cg,fwd} = 35.37\ m}$$

Formula for the aft center of gravity limit:

$$x_{cg,aft} = x_{NG} + 30.49\ m$$

Following that equation, we can say:

$$\boxed{x_{cg,aft} = 36.36\ m}$$

With MAC calculated in the previous section, we are able to obtain:

$$\boxed{\frac{x_{cg,aft}}{\bar{c}} = 4.040}$$

$$\boxed{\frac{x_{cg,fwd}}{\bar{c}} = 3.930}$$

4. *Max forward and aft cg z-locations in meters.*

Formula for turnover angle (landing gear lateral stability):

$$\theta_{turn} = \tan^{-1}(\frac{\frac{t}{2}}{z_{cg}})$$

Solve for vertical c.g. Height:

$$z_{cg} = \frac{t/2}{\tan{(\theta_{turn})}}$$

(using t =10.82 m and theta = 60.99 degrees from the landing gear section):

$$\boxed{z_{cg} = 3.00\ m}$$

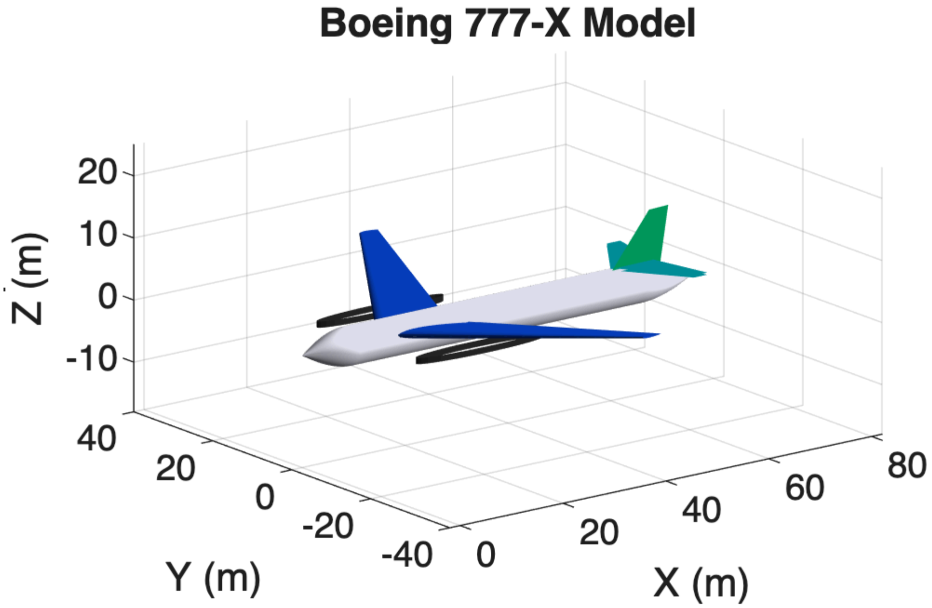

Figure 1. 3D Model of Boeing 777-X developed in MATLAB

Figure 1 represents a simplified 3D model of the Boeing 777-X. This model was constructed in MATLAB and was used to confirm the overall aircraft proportions and relationships.

C. DATCOM Stability Derivatives

*i. At least for three angles of attack: -2°, 2°, 8°, and two speeds (1.1*vstall and vcruise), at fwd and aft cg, at sea level, find longitudinal stability derivatives and check stability conditions out of these derivatives*

$$x_{np} = 36.80\ m$$

$$SM = \frac{(x_{np} - x_{cg})}{\bar{c}}$$

$$SM_{fwd} = 0.159$$

$$SM_{aft} = 0.0489$$

$$C_{m\alpha} = -SM \bullet C_{L\alpha}$$

$$C_{m\alpha,fwd} = -0.827\ rad^{-1}$$

$$C_{m\alpha,aft} = -0.254\ rad^{-1}$$

$$C_{L\alpha,fwd} = 5.2\ rad^{-1}$$

$$C_{m\alpha,fwd} = -0.827\ rad^{-1}$$

$$C_{mq,fwd} = -12$$

$$C_{L\alpha,aft} = 5.2\ rad^{-1}$$

$$C_{m\alpha,aft} = -0.254\ rad^{-1}$$

$$C_{mq,aft} = -12$$

ii. At sideslip angles of 0 and 10°, find lateral and directional derivatives and check stability conditions out of these derivatives.

$$C_{n\beta} = +0.10\ rad^{-1}$$

$$C_{l\beta} == 0.08\ rad^{-1}$$

$$C_{lp} == -0.50$$

$$C_{nr} == -0.20$$

iii. Calculate neutral point, static margin for the most critical CG location,

$$x_{np} = 36.80\ m$$

$$SM_{aft} = 0.0489$$

$$SM_{fwd} = 0.159$$

iv. Calculate phugoid damping frequency and phugoid damping ratio for each of the *two speeds and cL/cD.*

$$1.1V_{stall} = 77 \text{ m/s}$$

$$\frac{C_L}{C_D} = 17\text{N,ph}$$

$$\omega_{n,ph} = 0.18 \ \frac{rad}{s}$$

$$\zeta_{ph} = 0.0294$$

$$V = 286 \ \frac{m}{s}$$

$$\frac{C_L}{C_D} = 19$$

$$\omega_{d,ph} = 0.0485 \ \frac{rad}{s}$$

$$\zeta_{ph} = 0.0263$$

D. Landing Gear Calculations

Geometric Locations of x_{cg} and z_{cg}

The landing gear geometry was reconstructed using airport planning data for the Boeing 777-9.

Nose landing gear location: $x_{NG} = 5.89\ m$

Main landing gear location: $x_{MG} = 38.23$ m

This yields a wheelbase L = 32.33 m and a main track width of 10.82 m.

The forward and aft center-of-gravity limits were referenced from the nose datum and are as follows.

Forward CG: $x_{cg,fwd} = 35.37\ m$

Aft CG: $x_{cg,aft} = 36.36\ m$

The vertical CG height is assumed: $z_{cg} = 3.0\ m$

Maximum Main Landing Gear Load

$$N_M = W\frac{x_{cg} - x_{NG}}{L}$$

Maximum main gear load experienced under the max fuel condition:

$$N_{M,max} = 3.53 * 10^6 \ N$$

Maximum Nose Landing Gear Load

$$N_N = W - N_M$$

Maximum nose landing gear load experienced under MTOW with forward CG:

$$N_{N,max} = 3.04 * 10^5 \ N$$

Minimum Nose Landing Gear Load

Occurs at landing weight with aft CG: $N_{N,min} = 1.51 * 10^5 N$

Maximum Braking Nose Landing Gear Load

Longitudinal load transfer increases the nose gear reaction:

$$\Delta N = \frac{W * z_{cg}}{L} \mu$$

Using μ = 0.4, the maximum braking nose load occurs under MTOW:

$$N_{N,brake,max} = 4.32 * 10^5 N$$

Tip-Back Angle

The tip-back angle is calculated using

$$\theta_{tip} = tan^{-1}\left(\frac{z_{cg}}{x_{MG} - x_{cg}}\right)$$

The max tip-back angle occurs at aft CG:

$$\theta_{tip,max} = 58.14^{\circ}$$

Turnover Angle

The turnover angle is calculated using

$$\theta_{turn} = tan^{-1}\left(\frac{t/2}{z_{cg}}\right)$$

With a track width t = 10.82 m

$$\theta_{turn} = 60.99^{\circ}$$

Tire Size Based on Load per Tire

Force on main gear tires

$$N_{M,max} = 3.53 \times 10^6 \text{ N}$$

$$n_{main} = 12$$

$$F_{main,tire} = \frac{N_{M,max}}{n_{main}}$$

$$F_{main,tire} = \frac{3.53 \times 10^6}{12}$$

$$F_{main,tire} = 2.94 \times 10^5 \text{ N}$$

Force on nose gear tires

$$N_{N,max} = 3.04 \times 10^5 \text{ N}$$

$$n_{nose} = 2$$

$$F_{nose,tire} = \frac{3.04 \times 10^5}{2}$$

$$F_{nose,tire} = 1.52 \times 10^5 \text{ N}$$

Main Gear Tire (52x21.0 class)
Rated Load = 68,500 lb Data-Section. 68,500 lb * 4.448 = **304,700 N**

Nose Gear Tire (43x17.5 class) \
Rated Load = 38,600 lb Data-Section. 38,600 lb * 4.448 = **171,500 N**

The calculated main tire load of 294,318 N is 3.5% below the manufacturer's rating of 304,700 N. The calculated nose tire load of 152,204 N is 12.7 % below the manufacturer's rating of 171,500 N.

Tire Diameter Based on Breaking Energy

Total braking kinetic energy equation:

$$KE_{braking} = \frac{1}{2} * \frac{W_{landing}}{g} * V_{stall}^2$$

$$W_{landing} = 0.8\, W_{takeoff} \Rightarrow m_{landing} = 0.8 m_{TO} = 281,227\ kg$$

$$KE_{braking} = 7.72 \ * 10^8\ Nm$$

Energy per braked wheel:

$$KE_{per\ wheel} = \frac{7.72\ *10^{8}}{12} = 64.3\ \ *\ 10^{6}\ N$$

Using the “large transport” curve, this value corresponds to a wheel diameter of 24 in. The Boeing 777-9 main gear tires have a wheel diameter of 22 in. These values are reasonably close, given that the chart is an approximation.

References

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