Supporting Information

This is a [R Markdown](http://rmarkdown.rstudio.com) Notebook, provided as supporting information for the manuscript “Flight performance and wing morphology in the bat *Carollia perspicillata*: biophysical models and energetics”.

**For proper compilation, all data and function files provided need to be in the same folder.**

### Data Preparation and biophysical models

Start by loading required libraries

#Load required libraries  
require(paran)

## Loading required package: paran

## Loading required package: MASS

require(ggplot2)

## Loading required package: ggplot2

require(metR)

## Loading required package: metR

require(FactoMineR)

## Loading required package: FactoMineR

require(factoextra)

## Loading required package: factoextra

## Welcome! Want to learn more? See two factoextra-related books at https://goo.gl/ve3WBa

require(car)

## Loading required package: car

## Loading required package: carData

require(rsm)

## Loading required package: rsm

require(knitr)

## Loading required package: knitr

Next, the calculations of heat loss for separate body surfaces during flight are done, reading data frames and using the function provided in the file HeatLoss.R.

#Heat Loss calculation for each body part  
source("HeatLoss.R")  
#Read Body surface data  
bodyTA<-read.table("BodyTA.txt",header=T,row.names = 1)  
QtBody<-HLoss(bodyTA)  
HeadTA<-read.table("HeadTA.txt",header=T,row.names = 1)  
QtHead<-HLoss(HeadTA)  
WingTA<-read.table("WingTA.txt",header=T,row.names = 1)  
QtWing<-HLoss(WingTA)  
ArmTA<-read.table("ArmTA.txt",header=T,row.names = 1)  
QtArm<-HLoss(ArmTA)

Read wing morphology data, create a data frame with morphology variable for PCA, and calculate derived variables (AR, WL) and the total heat loss summing all body surfaces.

The morphological variable names are:

ID - Animal ID (color and necklace number)

Sex - sex factor: M = males, F = females

B - Wing span (m)

S - Wing Area (m^2) (sum of both sides plus bodyarea)

M - Body Mass (Kg)

ForL - Forearm length (mm)

WTip - Wing tip (Mm)

WLength - Wing length (mm)

DgIIIPh1 - Length of the 3rd digit of the 1st phalange (mm)

DgIIIPh2 - Length of the 3rd digit of the 2nd phalange (mm)

DgIIIPh3 - Length of the 3rd digit of the 3rd phalange (mm)

DgVMt - Length of the 5th digit of the metacarpal (mm)

DgVPh1- Length of the 5th digit of the 1st phalange (mm)

DgVPh2 - Length of the 5th digit of the 2nd phalange (mm)

Dactyl - Dactylopatagium width (mm)

Warea - Wing area (only left side) (mm^2)

DactArea - Dactylopatagium area (mm^2)

#read data, animal IDs are row names  
qt<-read.table("WingMorph.txt",header=T,row.names = 1)  
qt$Sex<-factor(qt$Sex)  
#Separate wing morphology variables for PCA  
Wing<-qt[,4:16]  
#Calculate aspect ratio  
qt$AR<-(qt$B^2)/qt$S  
#Calculate wing loading  
qt$WL<-(qt$M\*9.81)/qt$S  
#Add heat loss to main data frame, corrected for mechanical efficiency of 8.7%  
qt$Qt<-(QtBody$Qt+QtHead$Qt+QtWing$Qt+QtArm$Qt)/(1-0.087)

Calculate minimum power required to fly, using the function in file ‘PowFlight.R’, and add it to the main data frame.

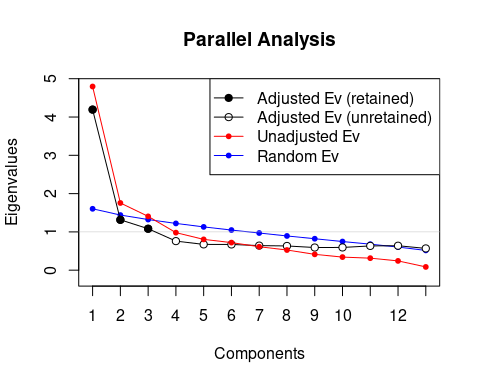
#Calculation of Pmin (minimum power required to fly horizontally)  
source("PowFlight.R")  
Powm<-PowFly(qt)  
qt$Pmin<-Powm$mP  
#MaxR = maximum range, not used in models because it is correlated with Pmin  
qt$MaxR<-Powm$MaxR  
#Vmp = minimum power speed, not used in models because it is correlated with Pmin  
qt$Vmp<-Powm$Vmp

### Principal components analysis of wing morphology

Calculate number of dimensions to retain using parallel analysis

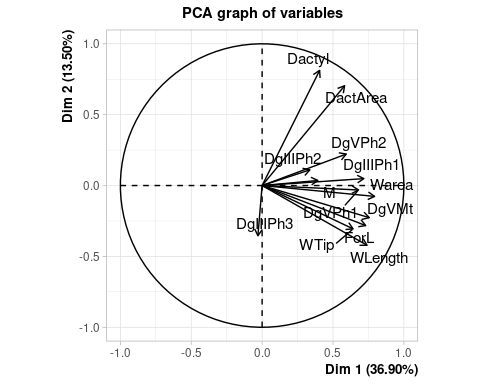
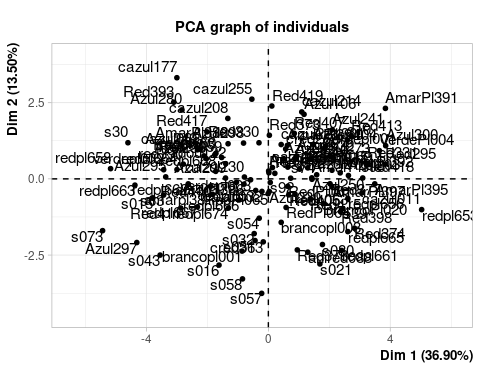
paran(Wing,graph=T,all=T)

##   
## Using eigendecomposition of correlation matrix.  
## Computing: 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%  
##   
##   
## Results of Horn's Parallel Analysis for component retention  
## 390 iterations, using the mean estimate  
##   
## --------------------------------------------------   
## Component Adjusted Unadjusted Estimated   
## Eigenvalue Eigenvalue Bias   
## --------------------------------------------------   
## 1 4.193537 4.796752 0.603214  
## 2 1.315121 1.754888 0.439766  
## 3 1.082590 1.405174 0.322584  
## 4 0.759339 0.980557 0.221218  
## 5 0.673924 0.804407 0.130483  
## 6 0.672237 0.720502 0.048265  
## 7 0.642355 0.612963 -0.02939  
## 8 0.632823 0.526721 -0.10610  
## 9 0.592402 0.413899 -0.17850  
## 10 0.593925 0.342076 -0.25184  
## 11 0.633948 0.314139 -0.31980  
## 12 0.639137 0.242730 -0.39640  
## 13 0.568655 0.085182 -0.48347  
## --------------------------------------------------   
##   
## Adjusted eigenvalues > 1 indicate dimensions to retain.  
## (3 components retained)



Parallel analysis identified 3 PCs with larger eigenvalues than expected in a random distribution. Next, generate a PCA object with 3 axes.

PCWing<-PCA(Wing,ncp=3)



Description of PCs, based on correlations with variables.

kables(list(kable("\*\*Correlations\*\*",col.names = NULL),kable(PCWing$var$cor),kable("\*\*Contribution (%)\*\*",col.names = NULL),kable(PCWing$var$contrib)),caption = "\*\*Table S1. Description of PCs (Dim.1-Dim.3), based on correlations of scores with variables, and the percentage contribution of each variable to the given component\*\*")

**Table S1. Description of PCs (Dim.1-Dim.3), based on correlations of scores with variables, and the percentage contribution of each variable to the given component**

|  |
| --- |
| **Correlations** |

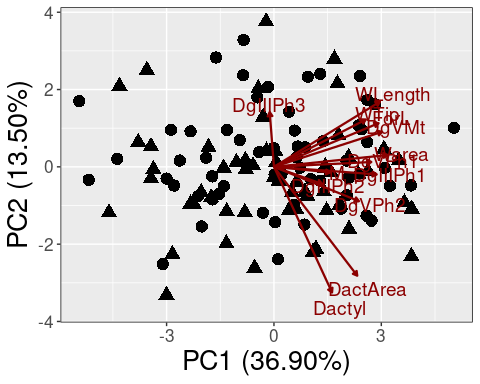
|  | Dim.1 | Dim.2 | Dim.3 |
| --- | --- | --- | --- |
| M | 0.3930441 | 0.0357618 | -0.1001526 |
| ForL | 0.7308137 | -0.2824303 | -0.1149222 |
| WTip | 0.6417254 | -0.3058741 | 0.2054238 |
| WLength | 0.7401456 | -0.4213380 | 0.1362644 |
| DgIIIPh1 | 0.7178556 | 0.0489367 | -0.1991975 |
| DgIIIPh2 | 0.3370307 | 0.1107531 | -0.6783921 |
| DgIIIPh3 | -0.0295857 | -0.3541331 | 0.7739853 |
| DgVMt | 0.7557868 | -0.2266024 | -0.0492903 |
| DgVPh1 | 0.6799445 | -0.0313326 | -0.1525218 |
| DgVPh2 | 0.5936091 | 0.2221052 | 0.0231415 |
| Dactyl | 0.4057258 | 0.8122598 | 0.3129717 |
| Warea | 0.7934823 | -0.0766917 | 0.1642200 |
| DactArea | 0.5819228 | 0.7038311 | 0.2665968 |

|  |
| --- |
| **Contribution (%)** |

|  | Dim.1 | Dim.2 | Dim.3 |
| --- | --- | --- | --- |
| M | 3.2205882 | 0.0728769 | 0.7138284 |
| ForL | 11.1343815 | 4.5454098 | 0.9398906 |
| WTip | 8.5852130 | 5.3313321 | 3.0031106 |
| WLength | 11.4205482 | 10.1160689 | 1.3214015 |
| DgIIIPh1 | 10.7430312 | 0.1364644 | 2.8238231 |
| DgIIIPh2 | 2.3680544 | 0.6989754 | 32.7515036 |
| DgIIIPh3 | 0.0182481 | 7.1463351 | 42.6319435 |
| DgVMt | 11.9083419 | 2.9260355 | 0.1728990 |
| DgVPh1 | 9.6382804 | 0.0559427 | 1.6555164 |
| DgVPh2 | 7.3460477 | 2.8110460 | 0.0381111 |
| Dactyl | 3.4317673 | 37.5958897 | 6.9707547 |
| Warea | 13.1258434 | 0.3351563 | 1.9192072 |
| DactArea | 7.0596546 | 28.2284672 | 5.0580102 |

#### Biplot for the space of the first two principal components

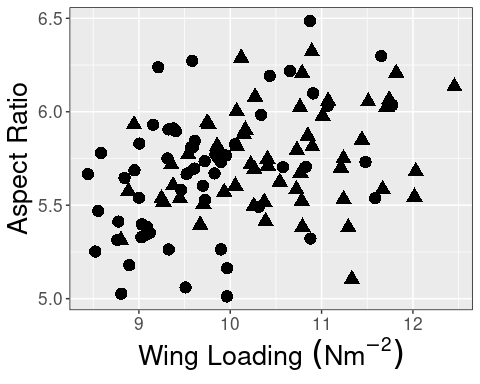
#Prepare data frames for biplot  
#Save variable coordinates  
PCvar<-as.data.frame(PCWing$var$coord[,1:3])  
#Invert PC2 variable coordinates for convenience of interpretation  
PCvar$Dim.2<--PCvar$Dim.2  
#Save individual scores  
PCind<-as.data.frame(PCWing$ind$coord[,1:3])  
#Invert PC2 individual scores for convenience of interpretation  
PCind$Dim.2<--PCind$Dim.2  
#PCA Biplot (Figure 3)  
#Create sex factor in numeric form to change point shape in plot  
Sexpch<-c(16,17)[as.numeric(qt$Sex)]  
#Biplot  
ggplot(PCind,aes(x=Dim.1,y=Dim.2))+  
 geom\_point(size=4,shape=Sexpch,)+  
 labs(y="PC2 (13.50%)", x="PC1 (36.90%)")+  
 geom\_text(data=PCvar\*4.5,label=variable.names(Wing),colour="darkred",size=5)+  
 geom\_segment(data=PCvar,  
 aes(x = 0, y = 0, xend = Dim.1\*4, yend = Dim.2\*4),  
 arrow = arrow(  
 length = unit(0.015,"npc"),   
 type="closed" # Describes arrow head (open or closed)  
 ),  
 colour = "darkred",  
 size = 0.8,  
 )+theme(text = element\_text(size=rel(4.5)),panel.border=element\_rect(linetype="solid",fill=NA))



### Other graphics

Scatterplot for aspect ratio and wing loading

#Scatterplot for aspect ratio and wing loading  
ggplot(qt,aes(x=WL,y=AR))+  
 geom\_point(size=4,shape=Sexpch,)+  
 labs(y="Aspect Ratio", x=expression(paste("Wing Loading "(Nm^-2))))+  
 theme(text = element\_text(size=rel(4.5)),panel.border=element\_rect(linetype="solid",fill=NA))



### Fitting response surface models (rsm package)

Independent variables in RSMs are standardized, so the model coefficients show changes in the response for each standard deviation of the predictor.

#Send PC scores to qt data frame, standardizing to sd=1  
qt$PC1<-scale(PCind$Dim.1)  
qt$PC2<-scale(PCind$Dim.2)  
qt$PC3<-scale(PCind$Dim.3)  
#Standardize AR and WL.  
qt$sAR<-scale(qt$AR)  
qt$sWL<-scale(qt$WL)

#### Response surface models for minimum power required to fly (Pmin) as response

Models fitting Pmin as response, Sex, AR and WL as predictors. We started fitting the model as second order

pwaw.rsm<-rsm(Pmin~Sex+SO(sAR,sWL),data=qt)  
kables(list(kable("\*\*Coefficients\*\*",col.names=NULL), kable(summary(pwaw.rsm)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(pwaw.rsm)$lof)), caption = "\*\*Table S2. Coefficients and analysis of variance of response surface model with Pmin as response and Sex, AR, and WL as predictors\*\*")

## Near-stationary-ridge situation detected -- stationary point altered  
## Change 'threshold' if this is not what you intend  
## Near-stationary-ridge situation detected -- stationary point altered  
## Change 'threshold' if this is not what you intend

**Table S2. Coefficients and analysis of variance of response surface model with Pmin as response and Sex, AR, and WL as predictors**

|  |
| --- |
| **Coefficients** |

|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 0.0606634 | 0.0005608 | 108.1674487 | 0.0000000 |
| SexM | -0.0000129 | 0.0006136 | -0.0210137 | 0.9832731 |
| sAR | -0.0037887 | 0.0002961 | -12.7975896 | 0.0000000 |
| sWL | 0.0076974 | 0.0003451 | 22.3049325 | 0.0000000 |
| sAR:sWL | -0.0009239 | 0.0003299 | -2.8007187 | 0.0060338 |
| sAR^2 | 0.0004849 | 0.0002299 | 2.1086880 | 0.0372623 |
| sWL^2 | 0.0004675 | 0.0002813 | 1.6620954 | 0.0993670 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| Sex | 1 | 0.0008487 | 0.0008487 | 100.365161 | 0.0000000 |
| FO(sAR, sWL) | 2 | 0.0055490 | 0.0027745 | 328.110021 | 0.0000000 |
| TWI(sAR, sWL) | 1 | 0.0000236 | 0.0000236 | 2.795881 | 0.0973751 |
| PQ(sAR, sWL) | 2 | 0.0000543 | 0.0000272 | 3.211301 | 0.0441461 |
| Residuals | 109 | 0.0009217 | 0.0000085 | NA | NA |
| Lack of fit | 109 | 0.0009217 | 0.0000085 | NaN | NaN |
| Pure error | 0 | 0.0000000 | NaN | NA | NA |

Model summary coefficients and analysis of variance indicate a quadratic component, so second order model is retained. Sex is removed from the model. It might be collinear with WL.

pwaw.rsm2<-rsm(Pmin~SO(sAR,sWL),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(pwaw.rsm2)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(pwaw.rsm2)$lof)), caption = "\*\*Table S3. Coefficients and analysis of variance of response surface model with Pmin as response and AR and WL as predictors\*\*")

## Near-stationary-ridge situation detected -- stationary point altered  
## Change 'threshold' if this is not what you intend  
## Near-stationary-ridge situation detected -- stationary point altered  
## Change 'threshold' if this is not what you intend

**Table S3. Coefficients and analysis of variance of response surface model with Pmin as response and AR and WL as predictors**

|  |
| --- |
| **Coefficients** |

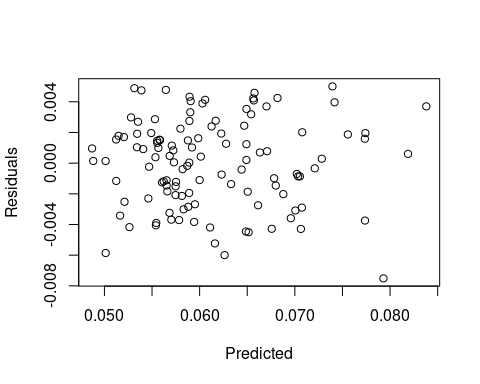
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 0.0606556 | 0.0004180 | 145.099172 | 0.0000000 |
| sAR | -0.0037885 | 0.0002945 | -12.862482 | 0.0000000 |
| sWL | 0.0076943 | 0.0003113 | 24.714144 | 0.0000000 |
| sAR:sWL | -0.0009240 | 0.0003284 | -2.813681 | 0.0058032 |
| sAR^2 | 0.0004858 | 0.0002244 | 2.165373 | 0.0325193 |
| sWL^2 | 0.0004680 | 0.0002788 | 1.678789 | 0.0960317 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| FO(sAR, sWL) | 2 | 0.0063967 | 0.0031984 | 381.705934 | 0.0000000 |
| TWI(sAR, sWL) | 1 | 0.0000221 | 0.0000221 | 2.632569 | 0.1075549 |
| PQ(sAR, sWL) | 2 | 0.0000568 | 0.0000284 | 3.390698 | 0.0372431 |
| Residuals | 110 | 0.0009217 | 0.0000084 | NA | NA |
| Lack of fit | 110 | 0.0009217 | 0.0000084 | NaN | NaN |
| Pure error | 0 | 0.0000000 | NaN | NA | NA |

Check model residuals for trends (no trends observed)

plot(predict(pwaw.rsm2),resid(pwaw.rsm2),xlab="Predicted",ylab = "Residuals")



Models fitting Pmin as response, Sex and PC scores as predictors. We started fitting model as second order, including the first three PCs:

pwpc.rsm<-rsm(Pmin~Sex+SO(PC1,PC2,PC3),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(pwpc.rsm)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(pwpc.rsm)$lof)), caption = "\*\*Table S4. Coefficients and analysis of variance of response surface model with Pmin as response and Sex and PC scores as predictors\*\*")

**Table S4. Coefficients and analysis of variance of response surface model with Pmin as response and Sex and PC scores as predictors**

|  |
| --- |
| **Coefficients** |

|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 0.0568601 | 0.0012349 | 46.0434340 | 0.0000000 |
| SexM | 0.0045790 | 0.0012854 | 3.5622360 | 0.0005544 |
| PC1 | 0.0021145 | 0.0006329 | 3.3408988 | 0.0011573 |
| PC2 | -0.0019698 | 0.0006708 | -2.9363502 | 0.0040813 |
| PC3 | -0.0012024 | 0.0006493 | -1.8517957 | 0.0668648 |
| PC1:PC2 | -0.0026303 | 0.0006671 | -3.9431467 | 0.0001454 |
| PC1:PC3 | 0.0006649 | 0.0006533 | 1.0176791 | 0.3111697 |
| PC2:PC3 | 0.0002733 | 0.0006733 | 0.4059267 | 0.6856225 |
| PC1^2 | -0.0005764 | 0.0005210 | -1.1064029 | 0.2710806 |
| PC2^2 | 0.0012071 | 0.0004385 | 2.7530370 | 0.0069587 |
| PC3^2 | 0.0015462 | 0.0004895 | 3.1586718 | 0.0020701 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| Sex | 1 | 0.0008487 | 0.0008487 | 19.577895 | 0.0000237 |
| FO(PC1, PC2, PC3) | 3 | 0.0005919 | 0.0001973 | 4.551439 | 0.0048649 |
| TWI(PC1, PC2, PC3) | 3 | 0.0005490 | 0.0001830 | 4.221429 | 0.0073385 |
| PQ(PC1, PC2, PC3) | 3 | 0.0008561 | 0.0002854 | 6.582840 | 0.0004038 |
| Residuals | 105 | 0.0045517 | 0.0000433 | NA | NA |
| Lack of fit | 105 | 0.0045517 | 0.0000433 | NaN | NaN |
| Pure error | 0 | 0.0000000 | NaN | NA | NA |

Model summary coefficients and the analysis of variance indicate a quadratic component, so the second order model is retained. PC3 did not contribute to surface (coefficients not statistically significant), so it was excluded.

pwpc.rsm2<-rsm(Pmin~Sex+SO(PC1,PC2),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(pwpc.rsm2)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(pwpc.rsm2)$lof)), caption = "\*\*Table S5. Coefficients and analysis of variance of response surface model with Pmin as response and PC scores as predictors\*\*")

**Table S5. Coefficients and analysis of variance of response surface model with Pmin as response and PC scores as predictors**

|  |
| --- |
| **Coefficients** |

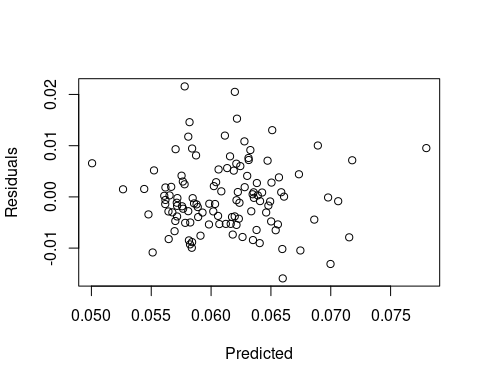
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 0.0582617 | 0.0011466 | 50.8119168 | 0.0000000 |
| SexM | 0.0044604 | 0.0013225 | 3.3726618 | 0.0010313 |
| PC1 | 0.0020258 | 0.0006626 | 3.0573891 | 0.0028090 |
| PC2 | -0.0017650 | 0.0006889 | -2.5622223 | 0.0117657 |
| PC1:PC2 | -0.0020339 | 0.0006784 | -2.9979953 | 0.0033666 |
| PC1^2 | -0.0004974 | 0.0005390 | -0.9229185 | 0.3580882 |
| PC2^2 | 0.0013193 | 0.0004581 | 2.8797220 | 0.0047925 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| Sex | 1 | 0.0008487 | 0.0008487 | 17.743813 | 0.0000522 |
| FO(PC1, PC2) | 2 | 0.0005659 | 0.0002830 | 5.916014 | 0.0036377 |
| TWI(PC1, PC2) | 1 | 0.0003255 | 0.0003255 | 6.805133 | 0.0103648 |
| PQ(PC1, PC2) | 2 | 0.0004438 | 0.0002219 | 4.638899 | 0.0116552 |
| Residuals | 109 | 0.0052135 | 0.0000478 | NA | NA |
| Lack of fit | 109 | 0.0052135 | 0.0000478 | NaN | NaN |
| Pure error | 0 | 0.0000000 | NaN | NA | NA |

Check model residuals for trends (no trends observed)

plot(predict(pwpc.rsm2),resid(pwpc.rsm2),xlab="Predicted",ylab = "Residuals")



#### Response surface models for heat loss (Qt) as response

Models fitting Qt as response, Sex, AR and WL as predictors. We started fitting model as second order

qtaw.rsm<-rsm(Qt~Sex+SO(sWL,sAR),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(qtaw.rsm)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(qtaw.rsm)$lof)), caption = "\*\*Table S6. Coefficients and analysis of variance of response surface model with Qt as response and Sex, AR, and WL as predictors\*\*")

**Table S6. Coefficients and analysis of variance of response surface model with Qt as response and Sex, AR, and WL as predictors**

|  |
| --- |
| **Coefficients** |

|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 4.3143781 | 0.1640823 | 26.2939892 | 0.0000000 |
| SexM | -0.0137608 | 0.1795265 | -0.0766504 | 0.9390421 |
| sWL | 0.0741225 | 0.1009652 | 0.7341391 | 0.4644403 |
| sAR | 0.2089513 | 0.0866157 | 2.4123937 | 0.0175175 |
| sWL:sAR | -0.0785660 | 0.0965165 | -0.8140157 | 0.4174107 |
| sWL^2 | 0.0634960 | 0.0822901 | 0.7716117 | 0.4420140 |
| sAR^2 | 0.0796838 | 0.0672747 | 1.1844546 | 0.2388095 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| Sex | 1 | 0.2232533 | 0.2232533 | 0.3084403 | 0.5797769 |
| FO(sWL, sAR) | 2 | 7.1417316 | 3.5708658 | 4.9334062 | 0.0088908 |
| TWI(sWL, sAR) | 1 | 0.0061370 | 0.0061370 | 0.0084787 | 0.9268036 |
| PQ(sWL, sAR) | 2 | 1.2993613 | 0.6496806 | 0.8975802 | 0.4105453 |
| Residuals | 109 | 78.8956666 | 0.7238135 | NA | NA |
| Lack of fit | 109 | 78.8956666 | 0.7238135 | NaN | NaN |
| Pure error | 0 | 0.0000000 | NaN | NA | NA |

Model summary coefficients and the analysis of variance do not support sex or a quadratic component, so first order (linear) model is retained

qtaw.rsm2<-rsm(Qt~FO(sWL,sAR),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(qtaw.rsm2)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(qtaw.rsm2)$lof)), caption = "\*\*Table S7. Coefficients and analysis of variance of response surface model with Qt as response, AR and WL as predictors\*\*")

**Table S7. Coefficients and analysis of variance of response surface model with Qt as response, AR and WL as predictors**

|  |
| --- |
| **Coefficients** |

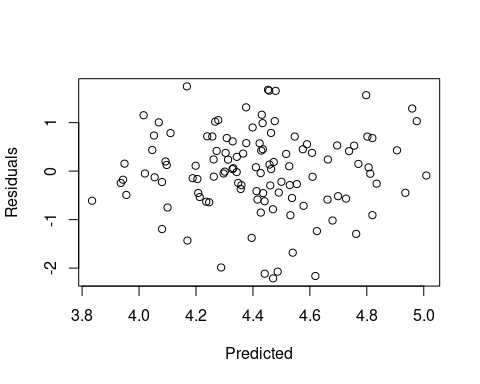
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 4.4212469 | 0.0782646 | 56.490998 | 0.0000000 |
| sWL | 0.1036763 | 0.0843771 | 1.228726 | 0.2217273 |
| sAR | 0.1945450 | 0.0843771 | 2.305661 | 0.0229542 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| FO(sWL, sAR) | 2 | 7.275038 | 3.6375191 | 5.119367 | 0.0074424 |
| Residuals | 113 | 80.291111 | 0.7105408 | NA | NA |
| Lack of fit | 113 | 80.291111 | 0.7105408 | NaN | NaN |
| Pure error | 0 | 0.000000 | NaN | NA | NA |

Checking residuals (no trends observed)

plot(predict(qtaw.rsm2),resid(qtaw.rsm2),xlab = "Predicted", ylab = "Residuals")



Fitting Qt as response, PC scores as predictors. First, fitting model as second order response:

qtpc.rsm<-rsm(Qt~Sex+SO(PC1,PC2,PC3),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(qtpc.rsm)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(qtpc.rsm)$lof)), caption = "\*\*Table S8. Coefficients and analysis of variance of response surface model with Qt as response and Sex and PC scores as predictors\*\*")

**Table S8. Coefficients and analysis of variance of response surface model with Qt as response and Sex and PC scores as predictors**

|  |
| --- |
| **Coefficients** |

|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 4.4491746 | 0.1523645 | 29.2008639 | 0.0000000 |
| SexM | 0.1713583 | 0.1585949 | 1.0804779 | 0.2824049 |
| PC1 | 0.0424398 | 0.0780893 | 0.5434777 | 0.5879530 |
| PC2 | 0.2914635 | 0.0827659 | 3.5215398 | 0.0006363 |
| PC3 | -0.0376005 | 0.0801107 | -0.4693564 | 0.6397881 |
| PC1:PC2 | -0.1040224 | 0.0823013 | -1.2639228 | 0.2090565 |
| PC1:PC3 | 0.0393790 | 0.0806052 | 0.4885416 | 0.6261850 |
| PC2:PC3 | -0.1372087 | 0.0830749 | -1.6516262 | 0.1015985 |
| PC1^2 | -0.0676508 | 0.0642771 | -1.0524868 | 0.2949924 |
| PC2^2 | 0.0068314 | 0.0540978 | 0.1262793 | 0.8997523 |
| PC3^2 | -0.0522853 | 0.0603947 | -0.8657258 | 0.3886143 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| Sex | 1 | 0.2232533 | 0.2232533 | 0.3383216 | 0.5620463 |
| FO(PC1, PC2, PC3) | 3 | 11.7852514 | 3.9284171 | 5.9531865 | 0.0008659 |
| TWI(PC1, PC2, PC3) | 3 | 5.0839760 | 1.6946587 | 2.5681130 | 0.0583382 |
| PQ(PC1, PC2, PC3) | 3 | 1.1857680 | 0.3952560 | 0.5989773 | 0.6170768 |
| Residuals | 105 | 69.2879010 | 0.6598848 | NA | NA |
| Lack of fit | 105 | 69.2879010 | 0.6598848 | NaN | NaN |
| Pure error | 0 | 0.0000000 | NaN | NA | NA |

Model summary coefficients and the analysis of variance do not support a quadratic component, so first order model is retained. Sex and PC3 did not contribute to surface (coefficients not statistically significant), so they were excluded from the model.

qtpc.rsm2<-rsm(Qt~FO(PC1,PC2),data=qt)  
kables(list(kable("\*\*Coefficients\*\*", col.names=NULL), kable(summary(qtpc.rsm2)$coefficients),kable("\*\*ANOVA\*\*",col.names=NULL), kable(summary(qtpc.rsm2)$lof)), caption = "\*\*Table S9. Coefficients and analysis of variance of response surface model with Qt as response and PC scores as predictors\*\*")

**Table S9. Coefficients and analysis of variance of response surface model with Qt as response and PC scores as predictors**

|  |
| --- |
| **Coefficients** |

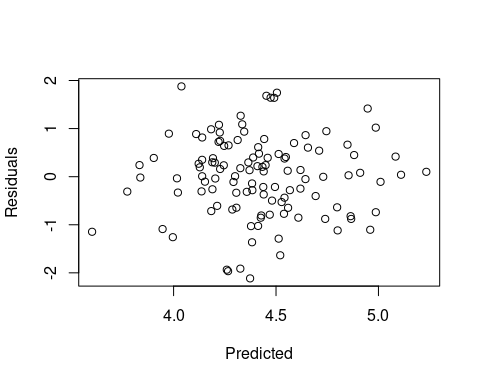
|  | Estimate | Std. Error | t value | Pr(>|t|) |
| --- | --- | --- | --- | --- |
| (Intercept) | 4.4212469 | 0.0768040 | 57.5652889 | 0.0000000 |
| PC1 | 0.0697330 | 0.0771372 | 0.9040119 | 0.3679123 |
| PC2 | 0.2901974 | 0.0771372 | 3.7620919 | 0.0002688 |

|  |
| --- |
| **ANOVA** |

|  | Df | Sum Sq | Mean Sq | F value | Pr(>F) |
| --- | --- | --- | --- | --- | --- |
| FO(PC1, PC2) | 2 | 10.24388 | 5.1219409 | 7.485286 | 0.0008855 |
| Residuals | 113 | 77.32227 | 0.6842679 | NA | NA |
| Lack of fit | 113 | 77.32227 | 0.6842679 | NaN | NaN |
| Pure error | 0 | 0.00000 | NaN | NA | NA |

Checking residuals (no trends observed)

plot(predict(qtpc.rsm2),resid(qtpc.rsm2),xlab = "Predicted", ylab = "Residuals")



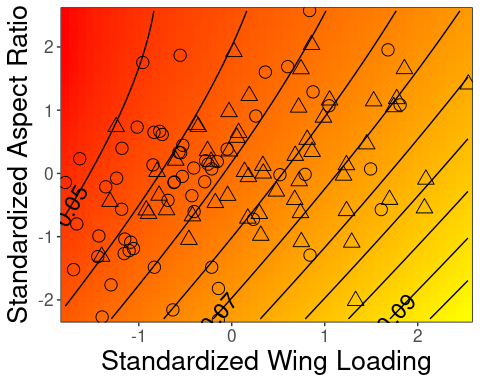
### Plotting response surface models

Generate new variables to predict surface

#Create new dataset based on min max AR and WL to predict rsm. Expanded grid with 50 points  
newAW<-expand.grid(sAR=seq(-2.30,2.57,length.out = 50),sWL=seq(-1.79,2.54,length.out = 50))  
#Calculate predictions  
newAW$Pmin<-predict(pwaw.rsm2,newAW)  
#Create new numeric vector to plot sex as different shapes  
Sexpch2<-c(1,2)[as.numeric(qt$Sex)]  
#Create new dataset based on min max PC scores to predict rsm. Expanded grid with 50 points  
newPC<-expand.grid(PC1=seq(-2.47,2.30,length.out = 50),PC2=seq(-2.50,2.80,length.out = 50))  
#Calculate predictions for males  
newPCM<-newPC  
newPCM$Sex<-rep("M",2500)  
newPCM$Pmin<-predict(pwpc.rsm2,newPCM)  
#Calculate predictions for females  
newPCF<-newPC  
newPCF$Sex<-rep("F",2500)  
newPCF$Pmin<-predict(pwpc.rsm2,newPCF)  
#Calculate average prediction  
newPC$Pmin<-round((newPCF$Pmin+newPCM$Pmin)/2,digits=5)  
#Calculate predictions for Qt models  
newAW$Qt<-predict(qtaw.rsm2,newAW)  
newPC$Qt<-predict(qtpc.rsm2,newPC)

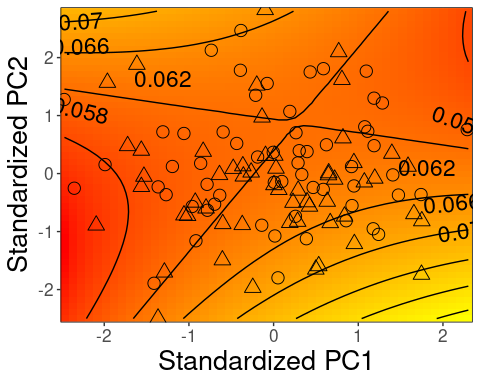
Generate contour plot for surface. Minimum power required to fly is the response, aspect ratio and wing loading are predictors

ggplot(newAW, aes(sWL,sAR, z = Pmin))+  
 labs(y="Standardized Aspect Ratio", x="Standardized Wing Loading")+  
 coord\_cartesian(xlim=c(-1.64,2.39), ylim=c(-2.13,2.40))+  
 geom\_raster(aes(fill = Pmin))+  
 geom\_contour(colour = "black")+  
 geom\_text\_contour(aes(z = Pmin), nudge\_x = 0,nudge\_y = 0, colour="black",size=6,breaks=seq(0.05,0.1,by=0.01))+  
 scale\_fill\_gradientn(colours=c("red","yellow"))+  
 geom\_point(data=qt,size=4,shape=Sexpch2,mapping=aes(x=sWL,y=sAR))+  
 theme(legend.position = "none",text = element\_text(size=rel(4.5)),panel.border=element\_rect(linetype="solid",fill=NA))



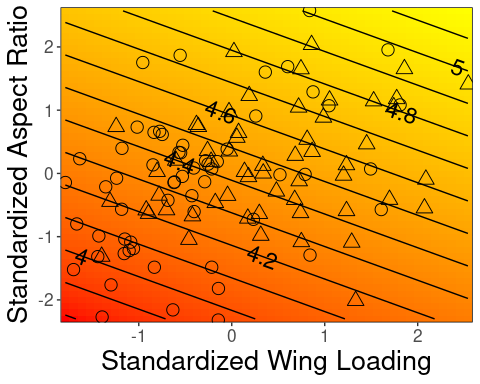
Generate contour plot for surface. Minimum power required to fly is the response, PC scores are predictors

ggplot(newPC, aes(PC1,PC2, z = Pmin))+  
 labs(y="Standardized PC2", x="Standardized PC1")+  
 coord\_cartesian(xlim=c(-2.295,2.13), ylim=c(-2.32,2.62))+  
 geom\_raster(aes(fill = Pmin))+  
 geom\_contour(colour = "black")+  
 geom\_text\_contour(aes(z = Pmin), nudge\_x = 0,nudge\_y = 0, colour="black",size=6,breaks=seq(0.058,0.072,by=0.002))+  
 scale\_fill\_gradientn(colours=c("red","yellow"))+  
 geom\_point(data=qt,size=4,shape=Sexpch2,mapping=aes(x=PC1,y=PC2))+  
 theme(legend.position = "none",text = element\_text(size=rel(4.5)),panel.border=element\_rect(linetype="solid",fill=NA))



Generate contour plot for surface. Heat loss (Qt) is the response, aspect ratio and wing loading are predictors

ggplot(newAW, aes(sWL,sAR, z = Qt))+  
 labs(y="Standardized Aspect Ratio", x="Standardized Wing Loading")+  
 coord\_cartesian(xlim=c(-1.64,2.39), ylim=c(-2.13,2.40))+  
 geom\_raster(aes(fill = Qt))+  
 geom\_contour(colour = "black")+  
 geom\_text\_contour(aes(z = Qt), nudge\_x = 0,nudge\_y = 0, colour="black",size=6)+  
 scale\_fill\_gradientn(colours=c("red","yellow"))+  
 geom\_point(data=qt,size=4,shape=Sexpch2,mapping=aes(x=sWL,y=sAR))+  
 theme(legend.position = "none",text = element\_text(size=rel(4.5)),panel.border=element\_rect(linetype="solid",fill=NA))



Generate contour plot for surface. Heat loss (Qt) is the response, PC scores are predictors

ggplot(newPC, aes(PC1,PC2, z = Qt))+  
 labs(y="Standardized PC2", x="Standardized PC1")+  
 coord\_cartesian(xlim=c(-2.29,2.13), ylim=c(-2.32,2.63))+  
 geom\_raster(aes(fill = Qt))+  
 geom\_contour(colour = "black")+  
 geom\_text\_contour(aes(z = Qt), nudge\_x = 0, nudge\_y = 0, colour="black",size=6)+  
 scale\_fill\_gradientn(colours=c("red","yellow"))+  
 geom\_point(data=qt,size=4,shape=Sexpch2,mapping=aes(x=PC1,y=PC2))+  
 theme(legend.position = "none",text = element\_text(size=rel(4.5)),panel.border=element\_rect(linetype="solid",fill=NA))

