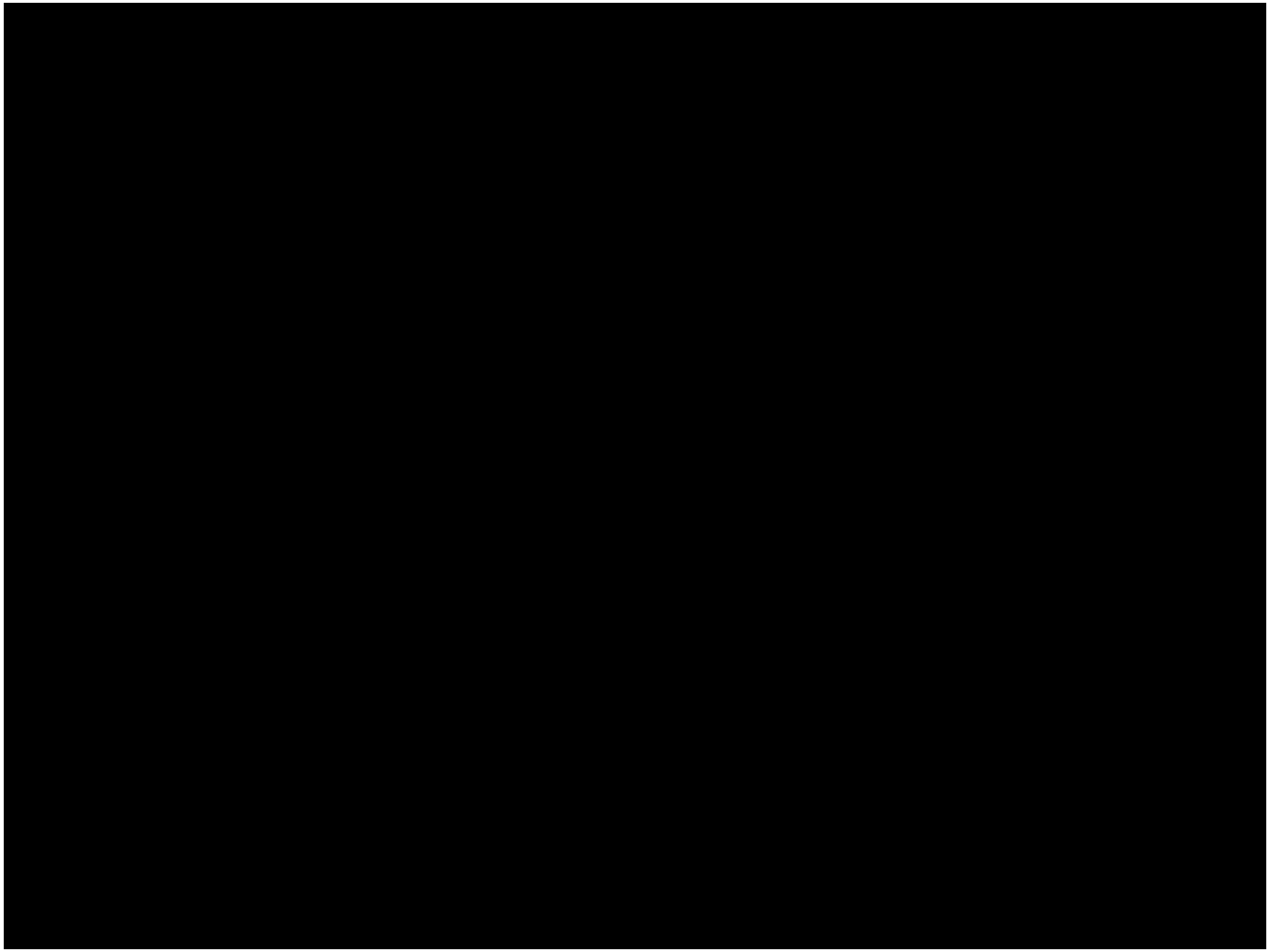
Planar pressure measurement

Truck blow down by wind

Planar pressure measurement

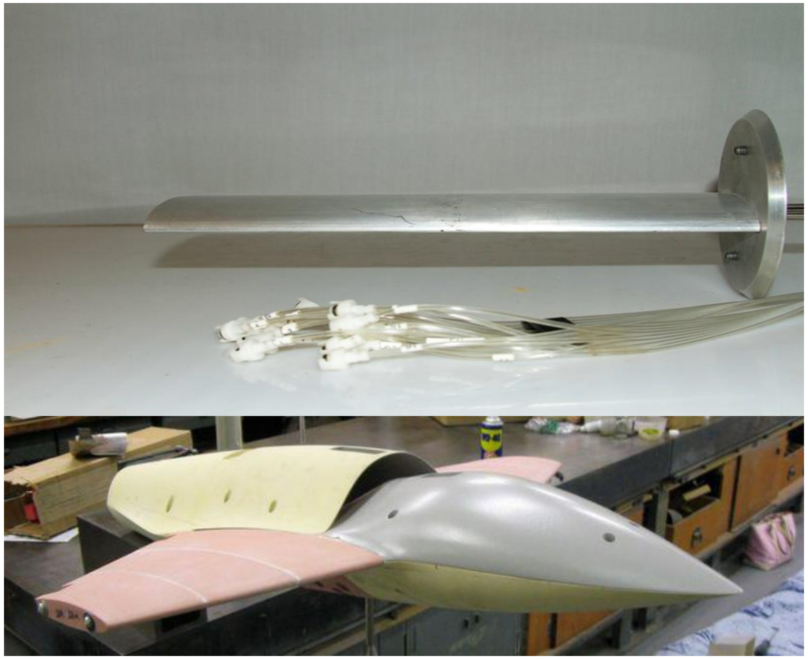
Boeing X48C Unmanned Aerial Vehicle in wind tunnel test

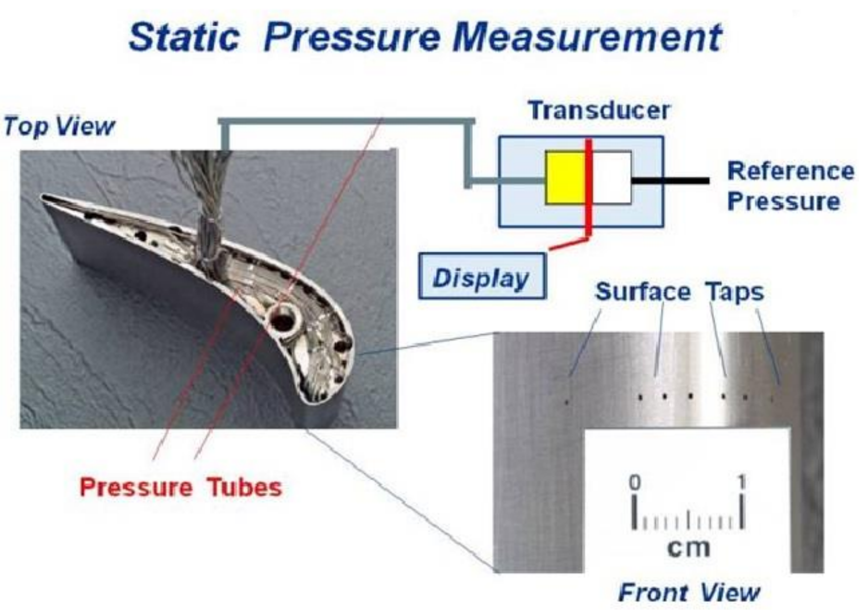


Pressure sensitive paint (PSP)

Traditionally, surface pressure is measured by **<u>pressure taps</u>**

1. Small holes need to be drilled on a model surface
2. Preparing the model is very time consuming and expensive
3. Pressure measured only at discrete points
4. Only suitable for stationary measurements

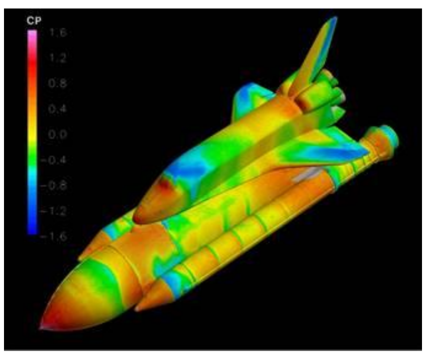


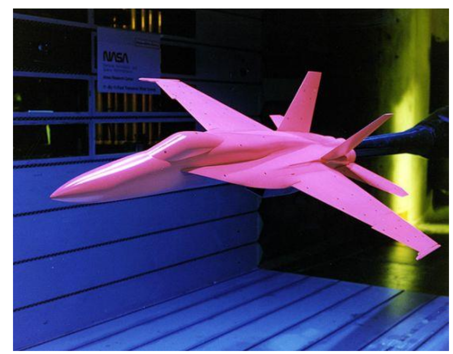


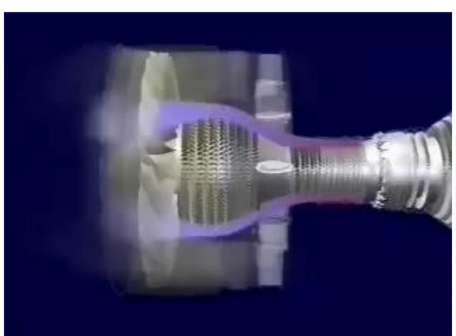
Pressure sensitive paint (PSP)

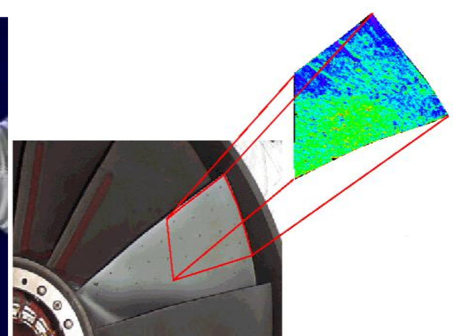
PSP, on the other hand, offers

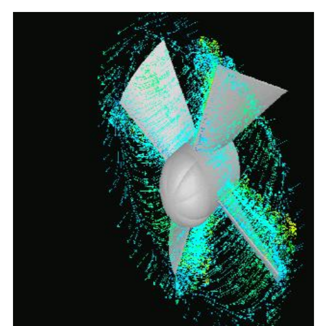
1. Non-contact, full field pressure measurement
2. Image based measurement technique provides much higher spatial resolution
3. Relatively easy to implement, cost effective
4. Suitable for both stationary and rotary measurements





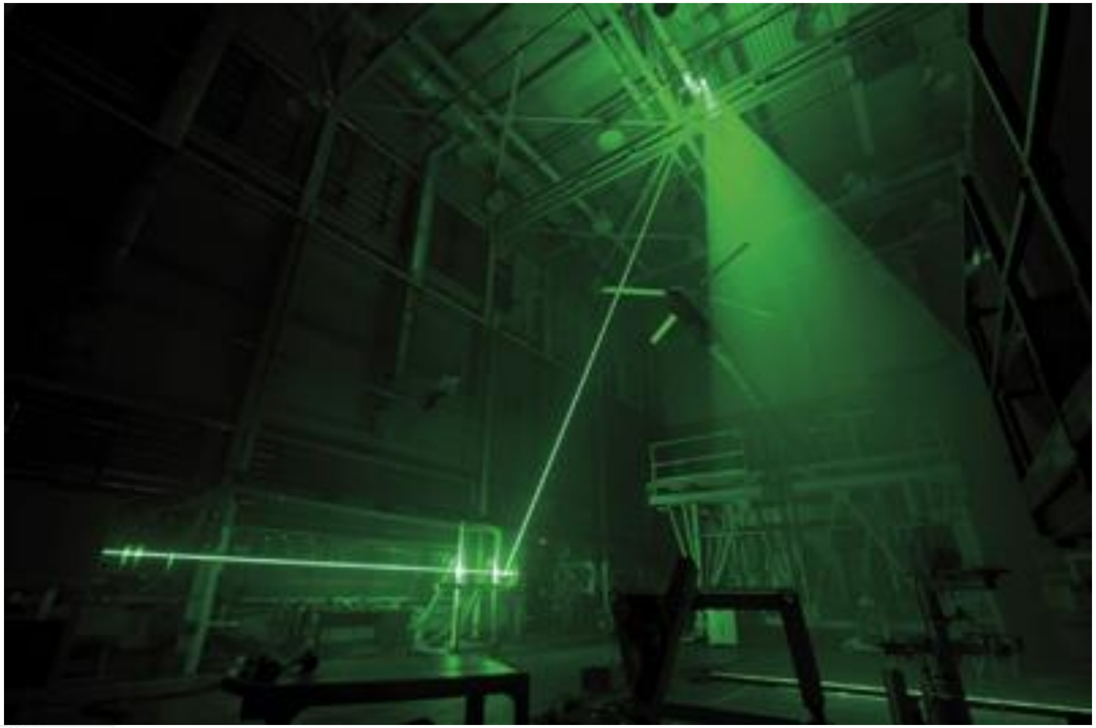


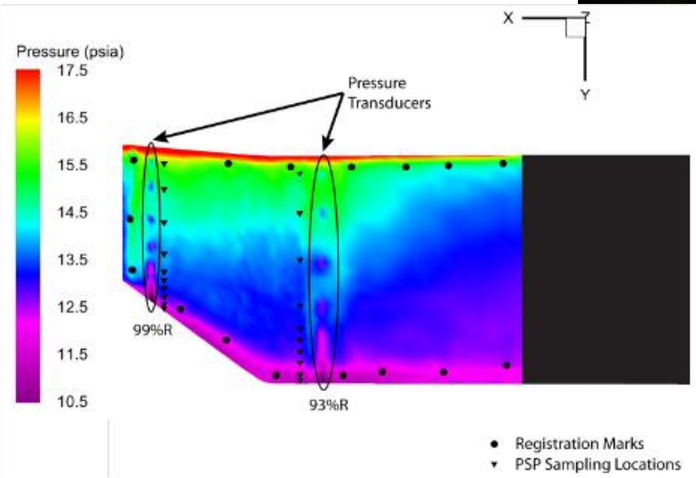


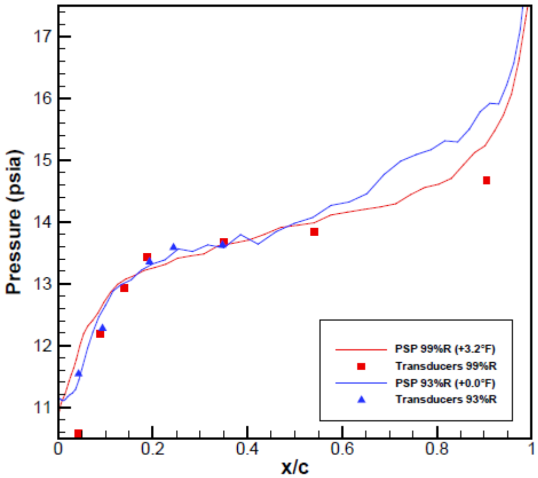


PSP measurements on a helicopter blade

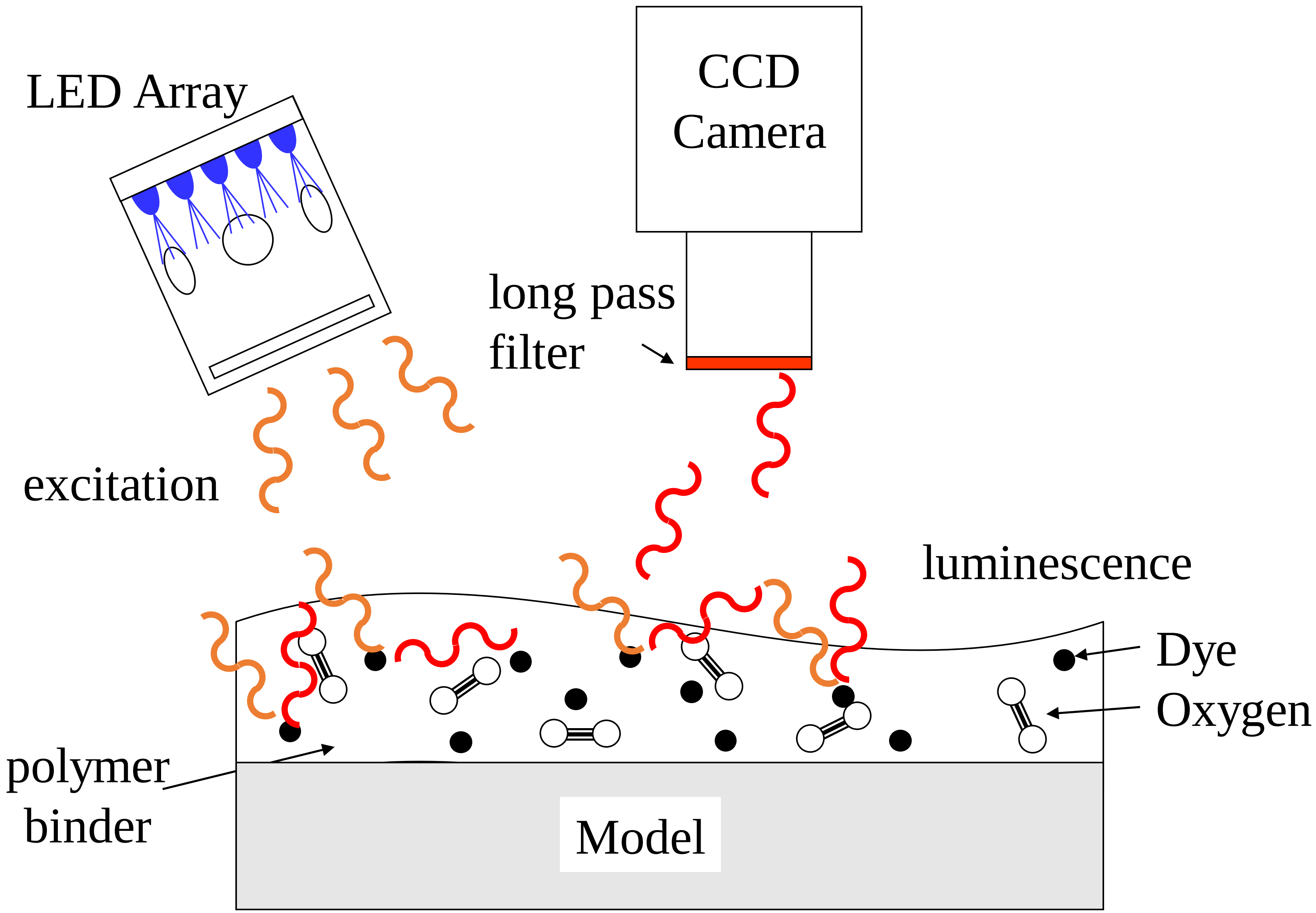
Large-scale rotor test at NASA Langley



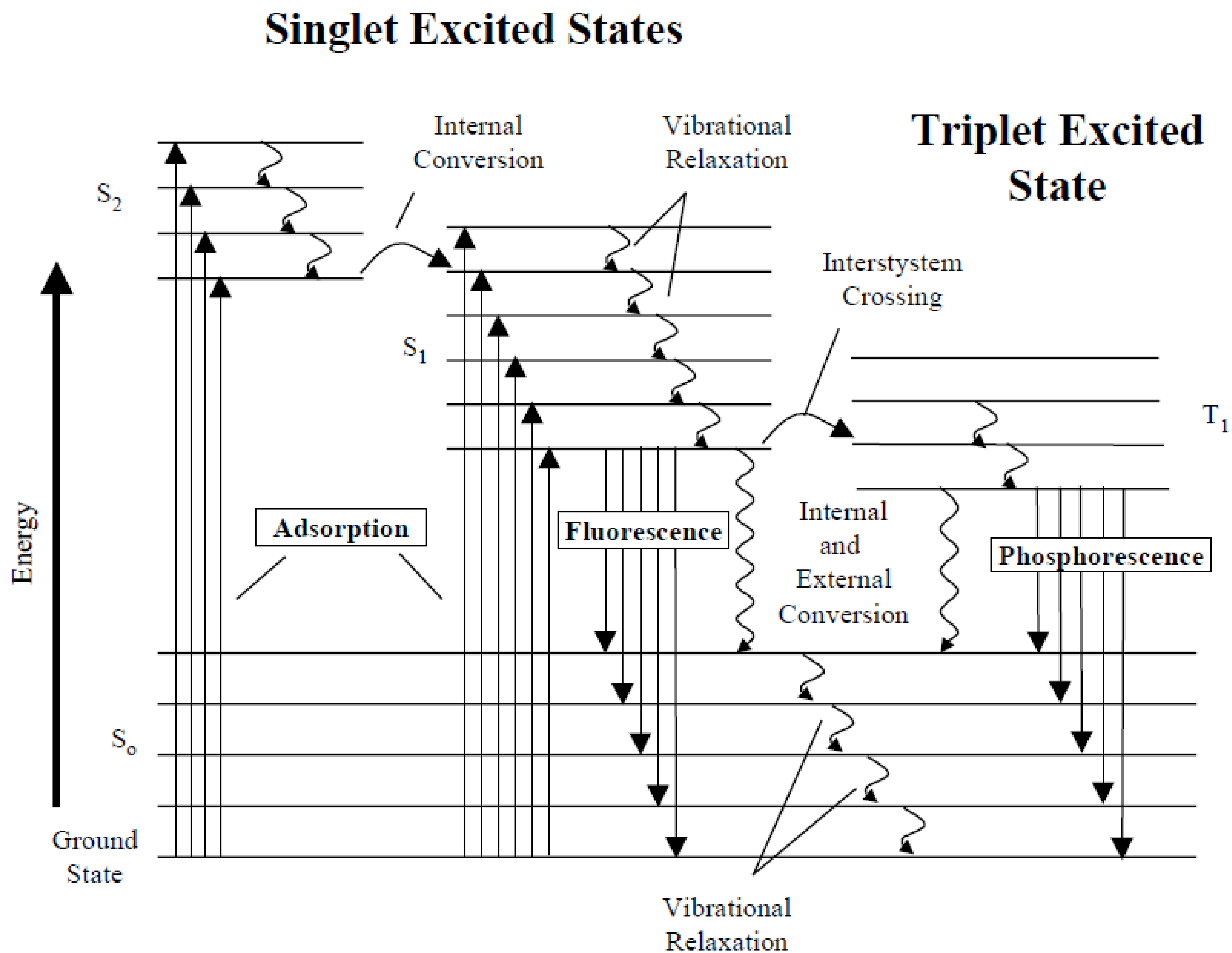




Pressure sensitive paint (PSP)



Basic Photophysics



Pressure sensitive paint (PSP)

<u>PSP consists of</u>

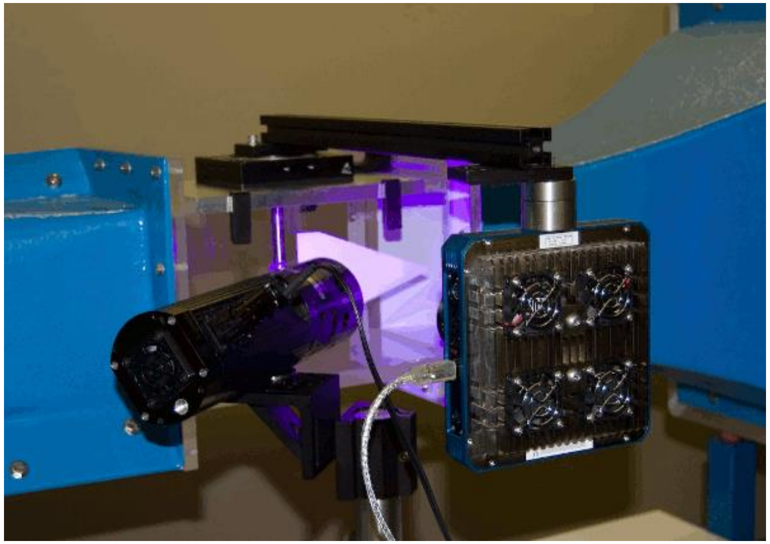
- Paint

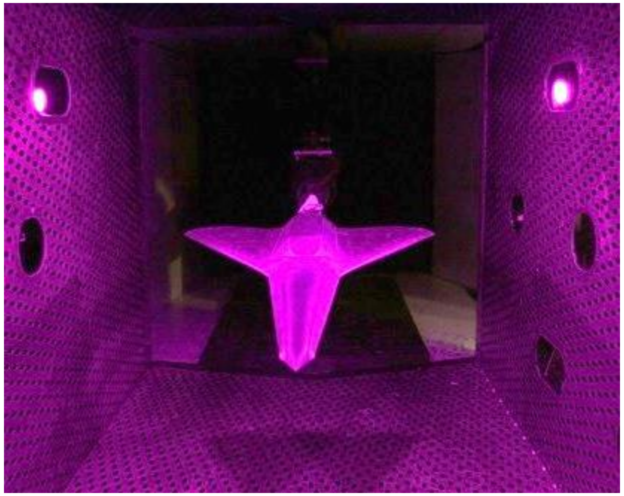
  luminophore, polymer binder (粘合剂), solvent

- Scientific grade camera
- Excitation light

  laser, UV lamps, xenon lamps, LED

- Data acquisition/processing unit





Principle

Stern-Volmer relation

➢ **Excitation**

Luminophore (发光基团) is excited by a photon from a ground state L0 to an excited state L*

$$L_0 + \hbar\nu \rightarrow L^*$$

➢ **Luminescent冷光radiation (**Fluorescence荧光, Phosphorescence磷光**)**

Excited luminophore returns to ground state via emitting energy

$$L^* \xrightarrow{k_r} L_0 + \hbar\nu_1$$

kr - rate constant for the radiation process

v1 - is the frequency of the luminescent emission

Principle

Stern-Volmer relation

- **Non-radiative process**

Excited luminophore returns to ground state by releasing heat

$$L^* \xrightarrow{k_{nr}} L_0 + \Delta$$

knr - rate constant for combined effect of all non-radiative process

- **Oxygen quenching**

$$L^* + O_2 \xrightarrow{k_q} L_0 + O_2^*$$

kq - rate constant quenching (淬灭) process

Principle

Stern-Volmer relation

- **Change rate of the population of excited state**

$$\frac{d[L^*]}{dt} = I_a - (\boxed{k_r +} k_{nr} + k_q[Q])[L^*]$$

Ia=ks1[L0]: rate of excitation

ks1: the excitation rate constant

[L0] is the population in the ground state

kr: the radiation rate constant

knr: non-radiation rate constant

kq: the quenching rate constant

[Q]: population of the oxygen (O_2)

- **At steady state**

$$d[L^*]/dt = 0 \qquad I_a = (k_r + \boxed{k_{nr} + k_q[Q])}[L^*]$$

Principle

<u>Stern-Volmer relation</u>

- **Non-radiative process (Arrhenius relation)**

$$k_{nr} = k_{nr0} + k_{nr1} \exp\left(-\frac{E_{nr}}{RT}\right)$$

knr0=knr(T=0) and knr1: rate constants for temperature-independ & temperature-dependent process, respectively

Enr: activation energy for the non-radiative process

R: universal gas constant

- **Oxygen quenching process (Smoluchowski relation)**

$$k_q = 4\pi R_{AB} N_0 D_0 \exp\left(-\frac{E_D}{RT}\right)$$

R_{AB}**:** interaction distance between the luminophore and oxygen molecules

D_0: diffusivity of oxygen molecules in the paint

E_D: activation energy for the oxygen diffusion process

Principle

Stern-Volmer relation

- **Luminescence efficient**

$$\Phi = \frac{rate\ of\ luminescence}{rate\ of\ excitation}$$

$$\Phi = \frac{k_r[L^*]}{I_a} = \boxed{\frac{k_r}{k_r + k_{nr} + k_q[Q]}} = \frac{I}{I_a}$$

$$\tau = \frac{1}{k_r + k_{nr} + k_q[Q]}$$

- **Relation of quenching and Pressure**

$$\frac{1}{\tau} = k_r + k_{nr0} + k_{nr1} exp(-\frac{E_{nr}}{RT}) + 4\pi R_{AB} N_0 D_0\ exp(-\frac{E_D}{RT}) \boxed{[O_2]_{polymer}}$$

Principle

<u>Stern-Volmer relation</u>

➢ **Relation of quenching and Pressure**

Oxygen population (Henry's law)

$$[O_2]_{polymer} = S\, p_{O_2} = S\, \phi_{O_2}\, p$$

<u>S</u>: oxygen solubility in a polymer binder

ϕ_{O_2} : mole fraction of oxygen in the testing gas (21%)

➢ **Simplify**

$$\frac{1}{\tau} = k_r + k_{nr0} + k_{nr1} exp(-\frac{E_{nr}}{RT}) + 4\pi R_{AB} N_0 D_0\, exp(-\frac{E_D}{RT})[O_2]_{polymer}$$

$$\frac{1}{\tau} = k_a + K\, p$$

$$k_a = k_r + k_{nr0} + k_{nr1} exp(-\frac{E_{nr}}{RT}) \qquad K = 4\pi R_{AB} N_0 P_0\, exp(-\frac{E_D}{RT})\phi_{O_2}$$

Principle

Stern-Volmer relation

$$\frac{I_{ref}}{I} = \frac{\tau_{ref}}{\tau} = A_{polymer}(T) + B_{polymer}(T)\frac{p}{p_{ref}}$$

$$A_{polymer} = A_{polymer,ref}\left[1 + \eta\frac{E_{nr}}{RT_{ref}}\left(\frac{T - T_{ref}}{T_{ref}}\right)\right] \qquad B_{polymer} = B_{polymer,ref}\left[1 + \frac{E_D}{RT_{ref}}\left(\frac{T - T_{ref}}{T_{ref}}\right)\right]$$

$$A_{polymer,\,ref} = \frac{1}{1 + K_{ref}\,p_{ref}/k_{aref}} \qquad B_{polymer,\,ref} = \frac{p_{ref}}{k_{aref}/K_{ref} + p_{ref}}$$

$$k_a = k_r + k_{nr0} + k_{nr1}\exp\left(-\frac{E_{nr}}{RT}\right) \qquad K = 4\pi R_{AB} N_0 P_0 \exp\left(-\frac{E_D}{RT}\right)\phi_{O_2}$$

$$\boldsymbol{A = 0.12} \qquad \boldsymbol{B = 0.88}$$

Apply the Stern-Volmer relation

1. Take image sequence when wind tunnel is off (Iref) Pref=P0
2. Take image sequence when wind tunnel is on (I)
3. A, B are predetermined and is constant for specific paint

   (assume temperature does not change)

Paint

➢ **Polymer binder**

1. Oxygen permeability
2. Temperature effect
3. humidity effect
4. adhesion
5. stability

➢ **Typical binders**

Silicon rubbers, GP-197, Silica gel

$$I_{ref} / I = A(T) + B(T) p / p_{ref}$$

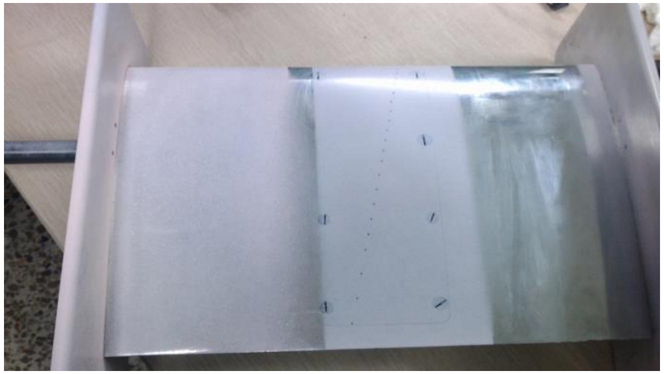
Luminophore	Binder	Excitation wavelength (nm)	Emission wavelength (nm)	Stern-Volmer coefficients A	Stern-Volmer coefficients B
H_2TSPP	silica gel	400	650, 709	0.58	0.42
$H_2(Me_2N)$TFPP	silica gel	400	650	0.43	0.56
H_2TCPP	silica gel	410	709	0.40	0.61
H_2TNMPP	silica gel	420	661, 714	0.43	0.60
H_2TTMAPP	silica gel	410	653, 710	0.40	0.60
Perylene dibutyrate	silica gel	457	520	0.33	0.67
Perylene dye	silica gel	480, 530	550, 570	0.47	0.53

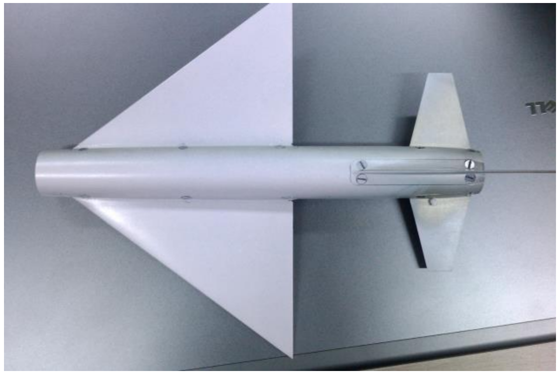
Paint

Applications of PSP

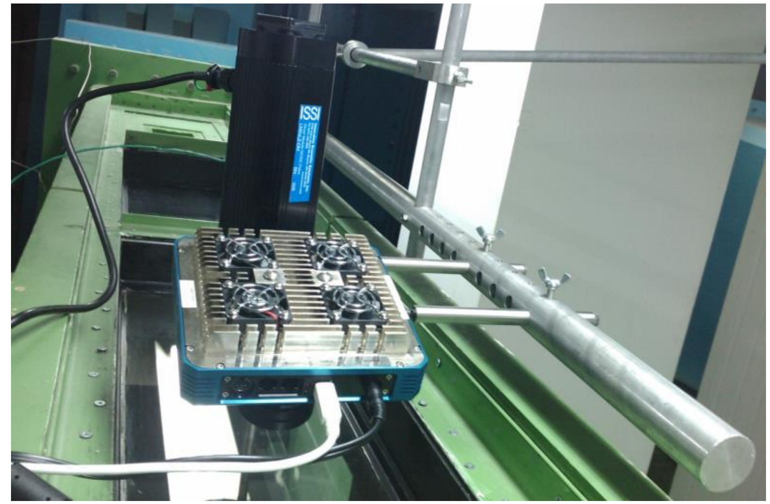
PSP tests in Tsinghua University

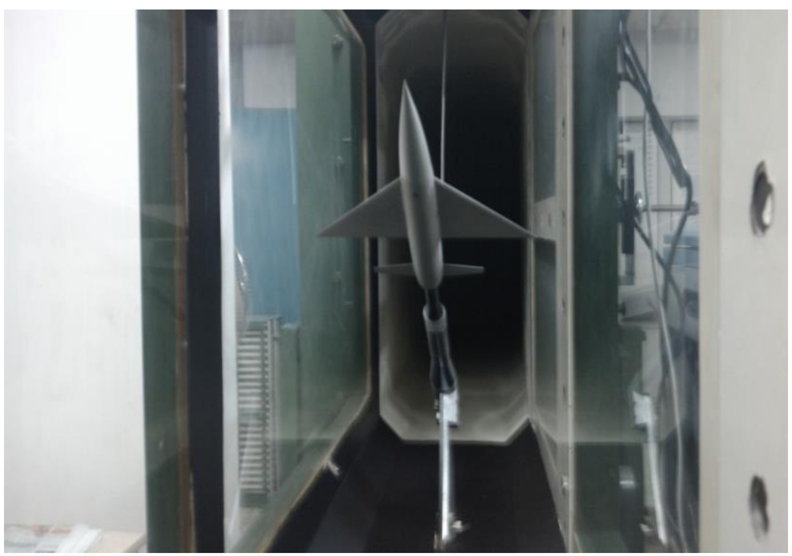
1. LED light (ISSI): intensity variation 0.1% per hour
2. Alta Apogee U2000 (512X512, 16bit)
3. UniCoat paint (ISSI)
4. Model: Delta wing, NACA0012 wing
5. Flow speed: 30m/s

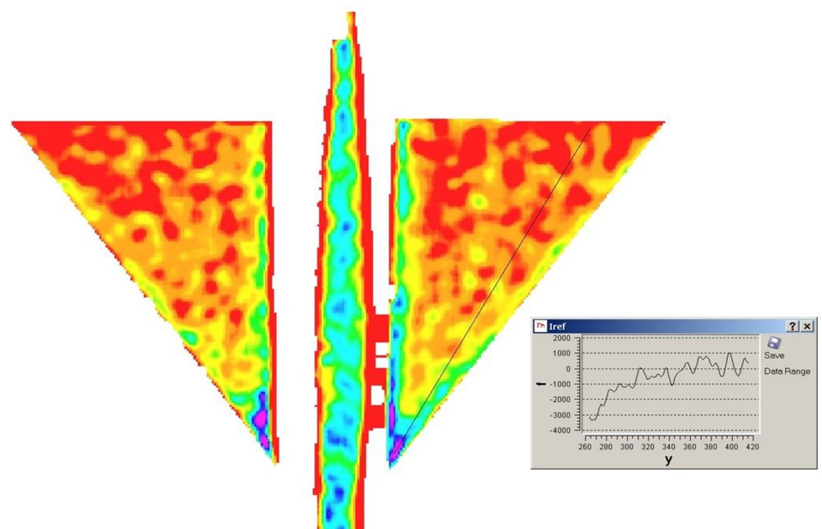




Applications of PSP







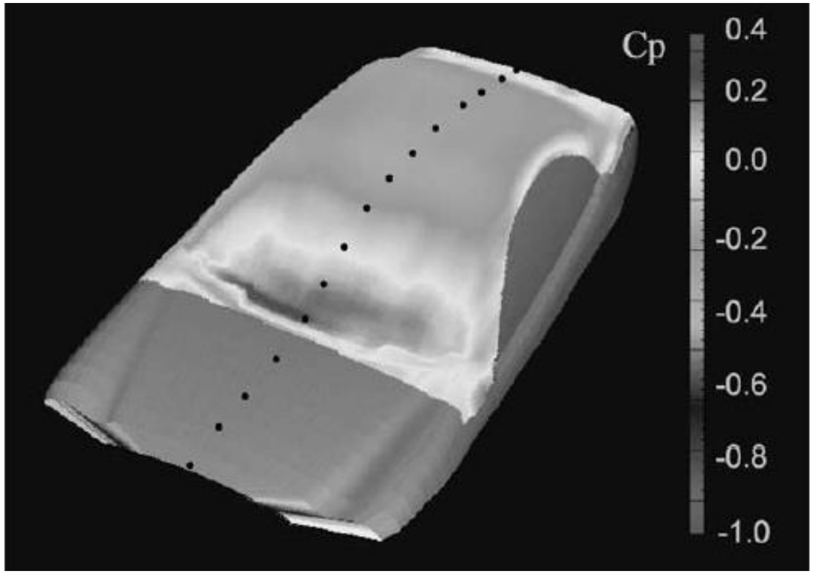
Applications of PSP

Pressure distribution on a Mercedes Benz car model

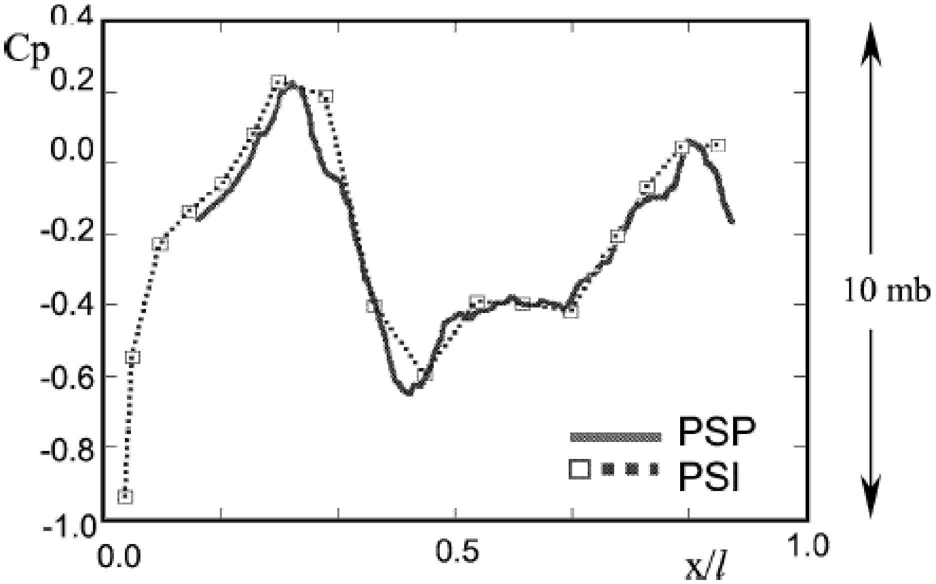
1. Xenon-flash lamp: 308nm, intensity variation <0.1%
2. Cooled CCD camera: 1340X1300 pixel
3. Paint developed by ONERA (法国宇航局)
4. Model: Mercedes Benz car model
5. Flow speed: 65m/s
6. 64 raw images were acquired

Applications of PSP

Pressure distribution on the car model surface



Pressure distribution along centre line



Accuracy: 0.0145psi

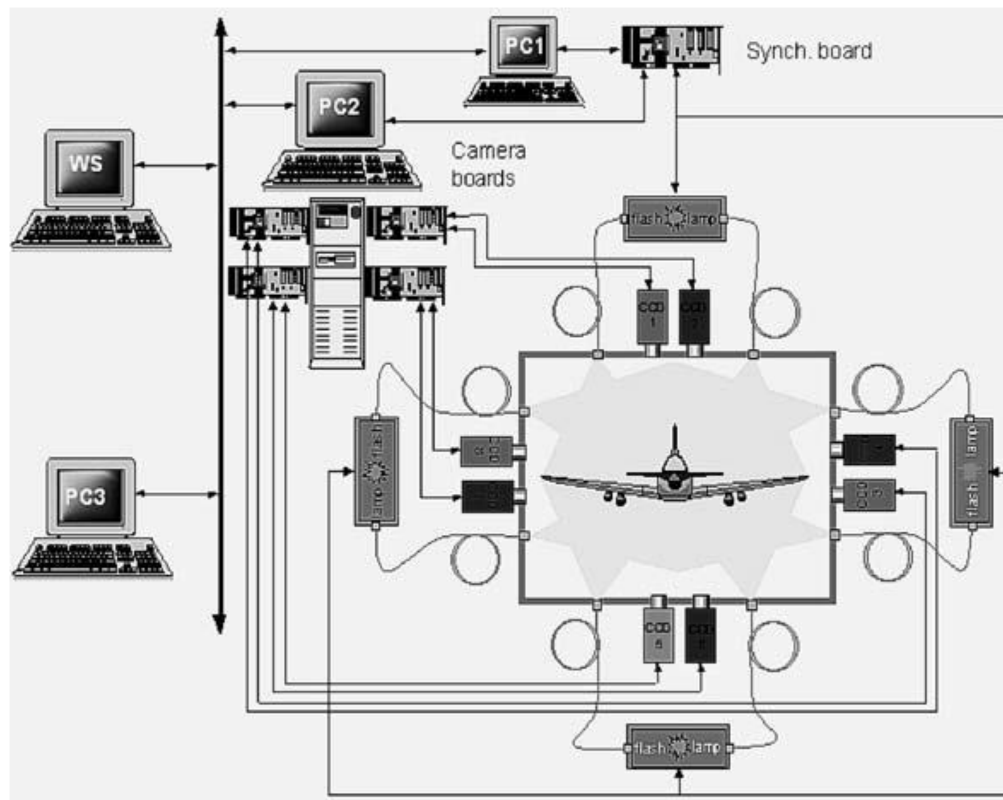
Applications of PSP

Aircraft model in transonic (跨音速) flow

1. 8 UV lights
2. 8 Cooled CCD camera: 12bit
3. Paint developed by DLR (德国宇航局)
4. Model: AerMacchi M-346 Advanced Trainer (教练机)
5. Flow speed: 0.6 ~ 0.95 March

   (1March=343.2m/s)

Applications of PSP



Applications of PSP