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Reliability-based Design of a Vibration Control System for Wind Turbines

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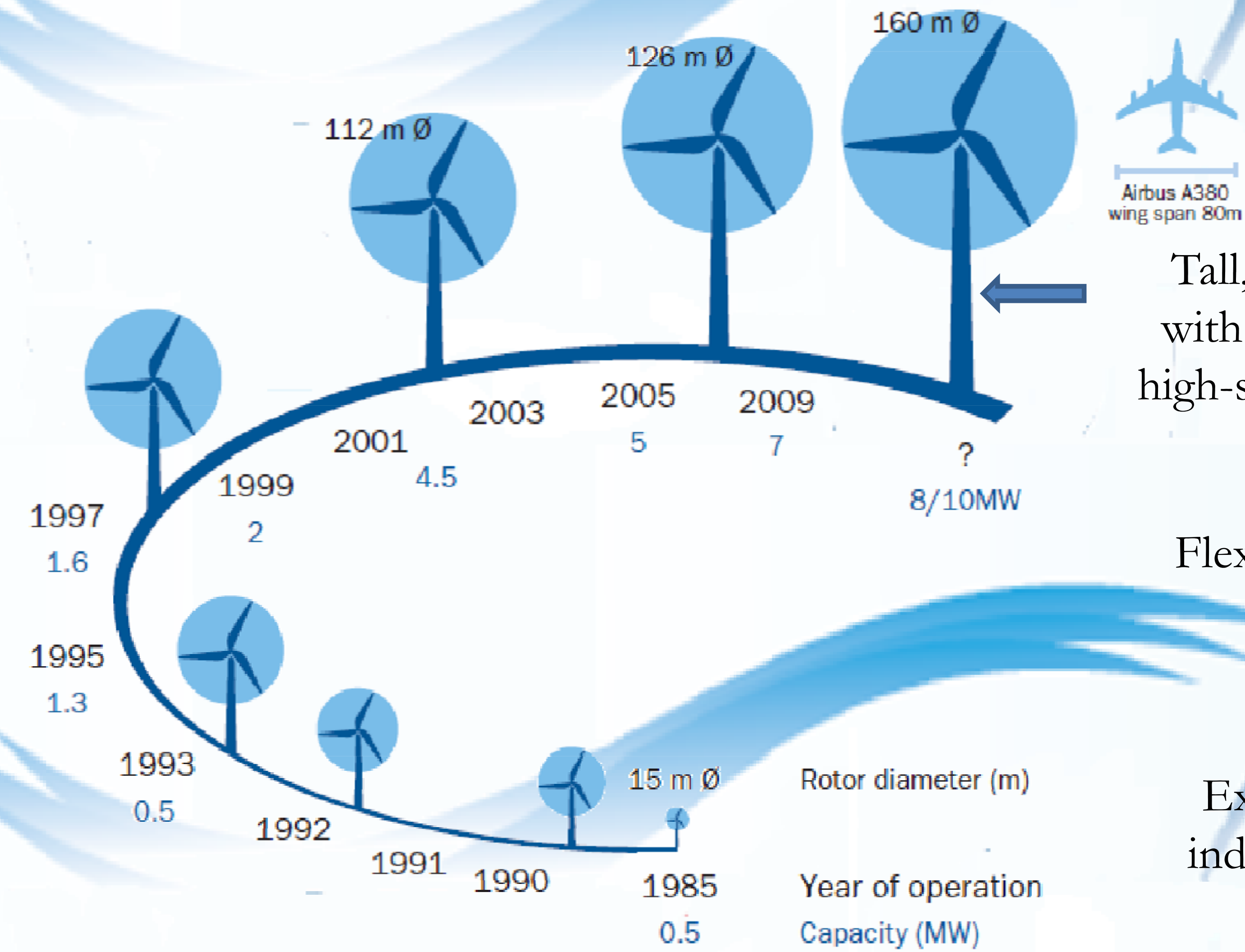
Size Evolution of Wind Turbines



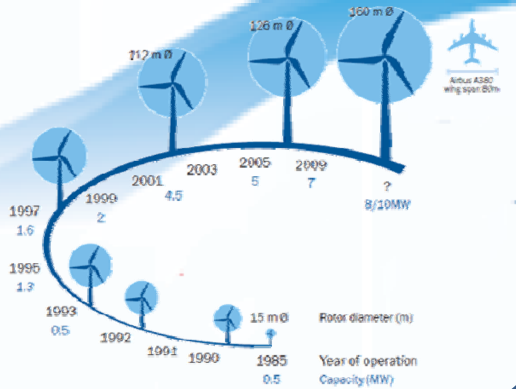
Tall, slender towers with lightweight and high-strength materials

Flexible and lightly damped

Excessive wind-induced vibration

Source: European Wind Energy Association, Factsheets, 2010

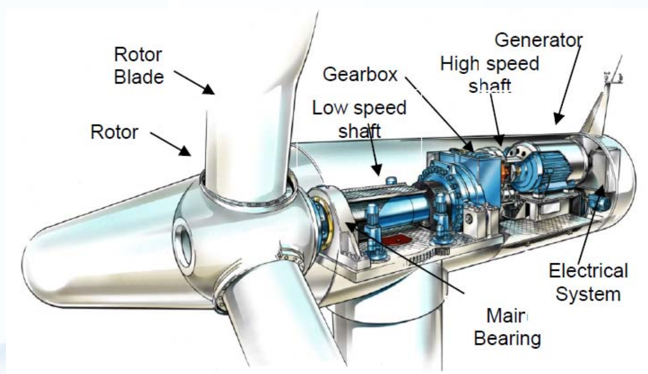
Motivation



Excessive Vibration

Inhibition of energy conversion

Collapse of tower



Damages to vibration sensitive components

Increased Risk
- Unavailability
- Low production
- Repair cost
- Lost revenue

Vibration control mechanism is essential!

Objective

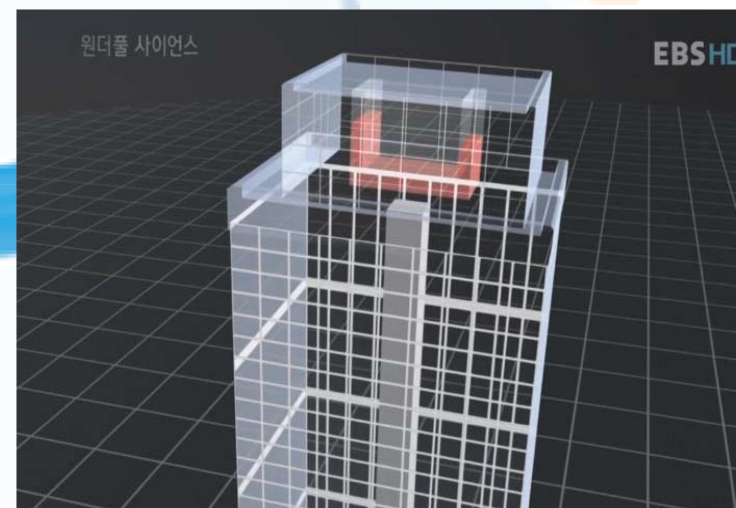
The study seeks to

- Demonstrate effectiveness of tuned liquid column damper (TLCD) in reducing dynamic responses of wind turbine towers

- Identify the effective design of TLCD, on the basis of reliability gains

Tuned Liquid Column Damper

- Passive vibration control device
- Relies on combined action of
  - Movement of liquid mass
  - Gravitation restoring force on liquid
  - Damping effect of orifice
- Widely used in buildings to mitigate earthquake- and wind-induced damages



Source: http://flash.lakeheadu.ca/~kliu/ and blog.naver.com

Response Simulation Framework

- Model follows a mathematical sub-structuring technique
  - Rotational effects of blades
  - Spatial correlation of drag force along tower
  - Blade/ tower interaction
- Generated stochastic winds
- Dynamic equations in a matrix form are formulated to describe the coupled motion and solved for responses.

Dynamic Simulation Model

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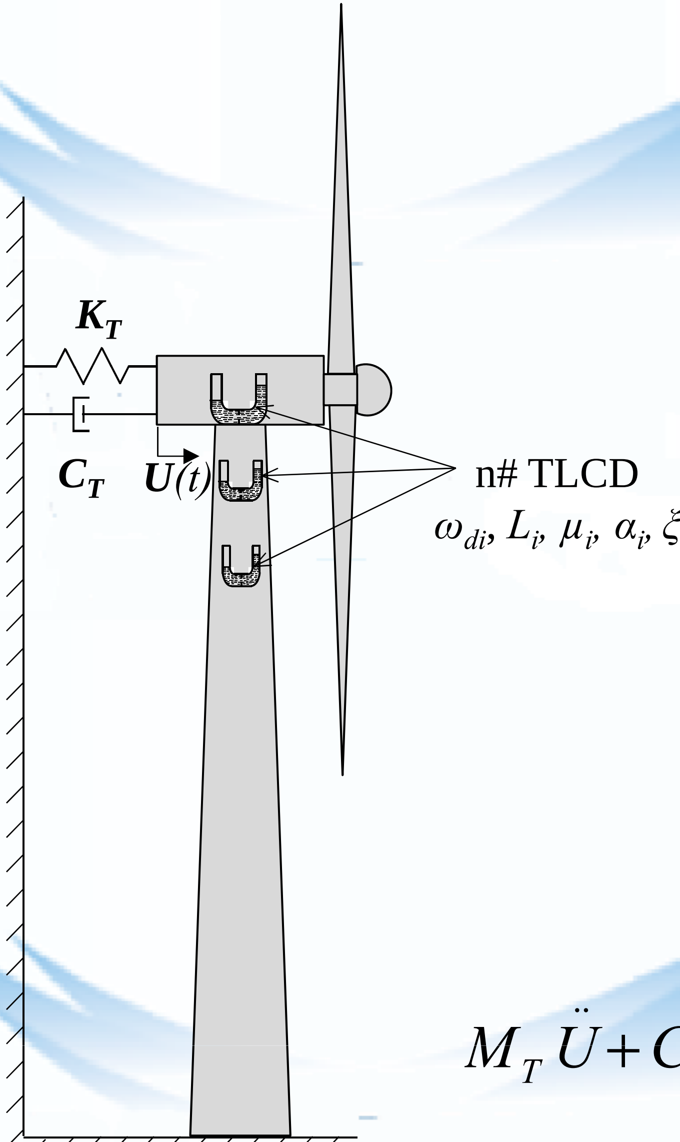
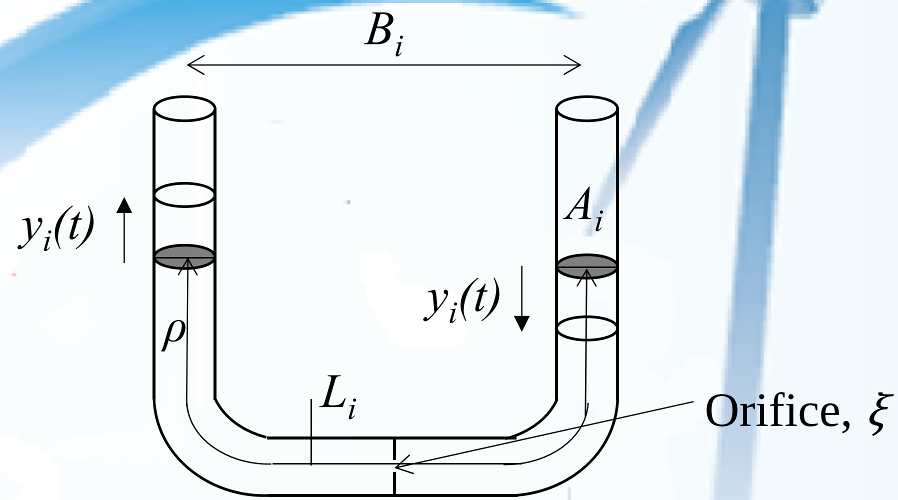




Motion of Liquid

$$\rho A_i L_i \ddot{y}_i + \frac{1}{2} \rho A_i \xi |\dot{y}_i| \dot{y}_i + 2g\rho A_i y_i = -\rho A_i B_i \ddot{u}_{ij}$$

Motion of TLCD equipped tower

$$M_T \ddot{U} + C_T \dot{U} + K_T U = F_T(t) + m_B \ddot{u}_1 T_1 - \sum \rho A_i B_i \ddot{y}_i T_1 - \sum \rho A_i L_i \ddot{u}_{ij} T_1$$

Wind Turbine Reliability Framework

- Fragility Approach
  - Reflect probabilities of exceeding predefined limit states at given wind speeds
  - Explores wide range of wind speeds
  - Explicitly integrates inherent uncertainties

$$P[d \geq D_{Ls} / v_w] = 1 - \Phi\left(\frac{In(D_{Ls}) - In(D_w)}{\beta}\right)$$

- Probability Demand Model

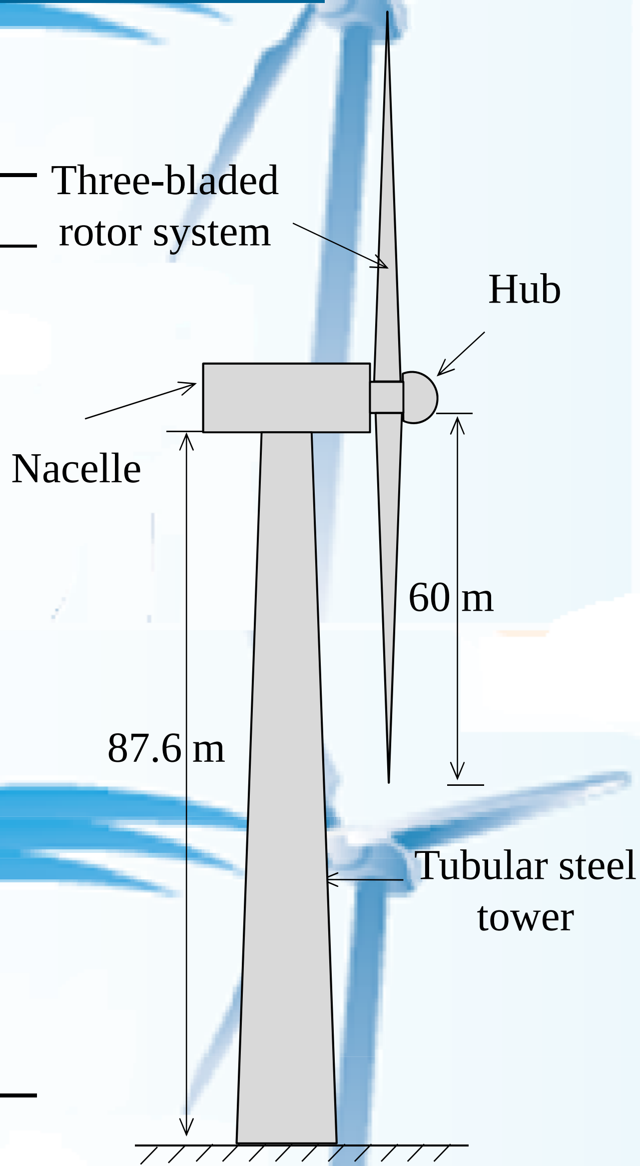
$$D_w = b(v_w)^c$$

Illustrative Example

- 5MW NREL Baseline Wind turbine

Property	Value
Rating	5 MW
Cut-in wind speed	3 m/s
Rated wind speed	11.4 m/s
Cut-out wind speed	25 m/s
Hub height	90 m
Tower height	87.6 m
Tower type	Tapered tubular/ steel
Tower width	6 m (base) 3.5 m (top)
Rotor diameter	126 m
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg

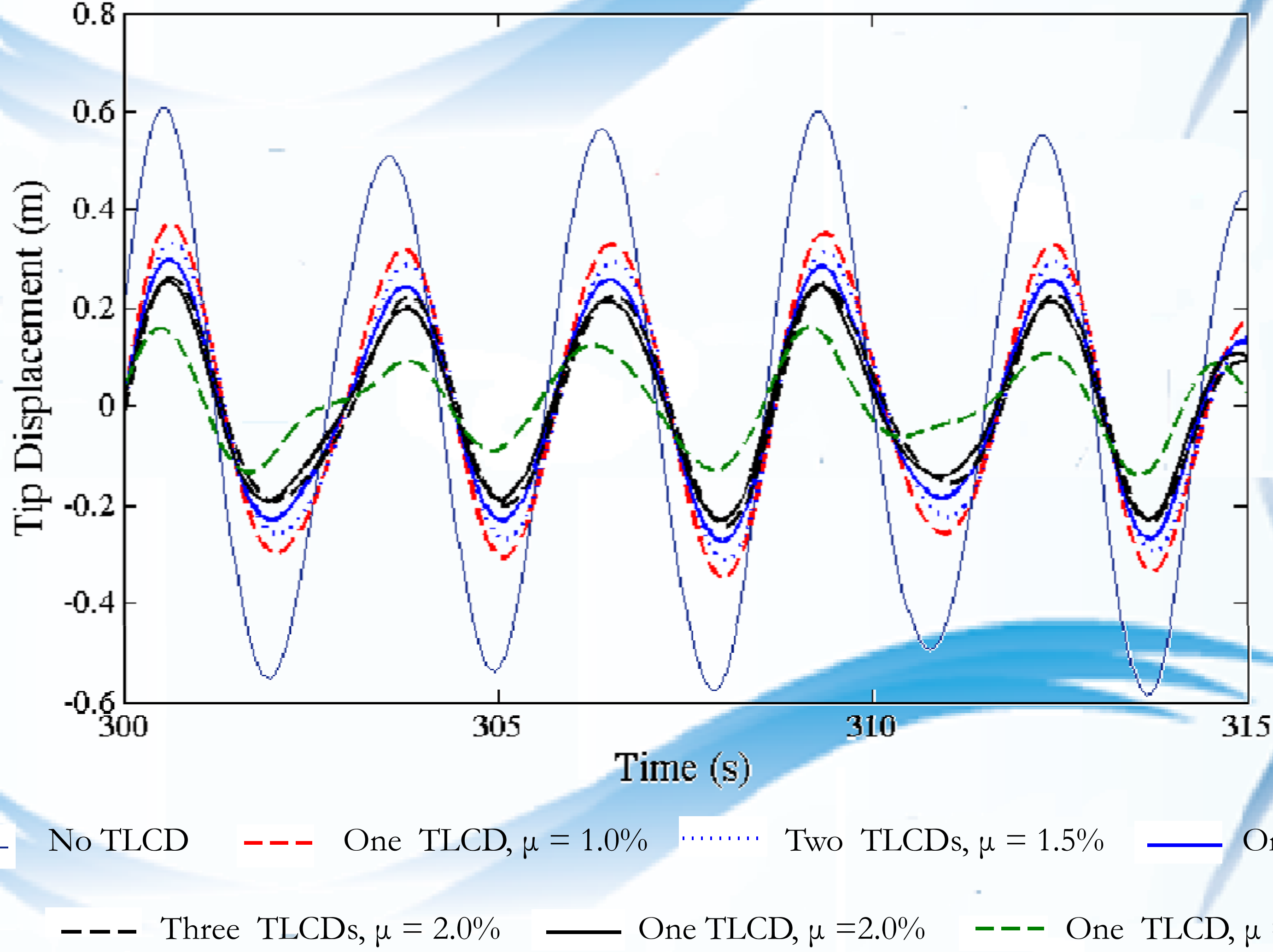
Source: Jonkman et al., 2009



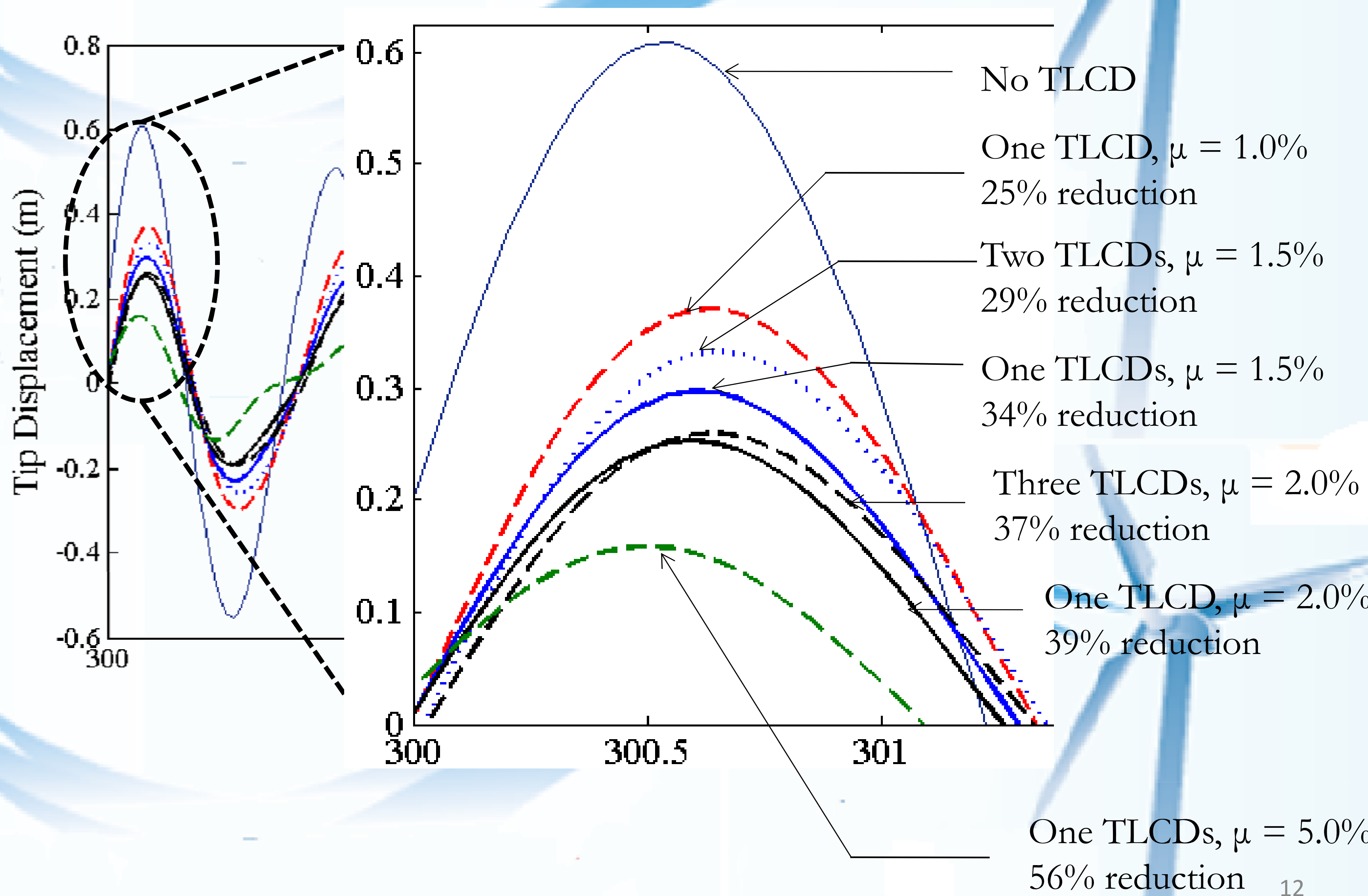
TLCD Configurations

	Position	Mass ratio (%)	Tuning (%)	Width (m)
One TLCD	Nacelle	1.0	98.5	3
Two TLCDs	Nacelle	1.0	98.5	3
	Tower	0.5	99.0	2
One TLCD	Nacelle	1.5	98.5	3
Three TLCDs	Nacelle	1.0	98.5	3
	Tower	0.5	99.0	2
	Tower	0.5	98.8	2
One TLCD	Nacelle	2.0	98.5	3
One TLCD	Nacelle	5.0	98.5	3

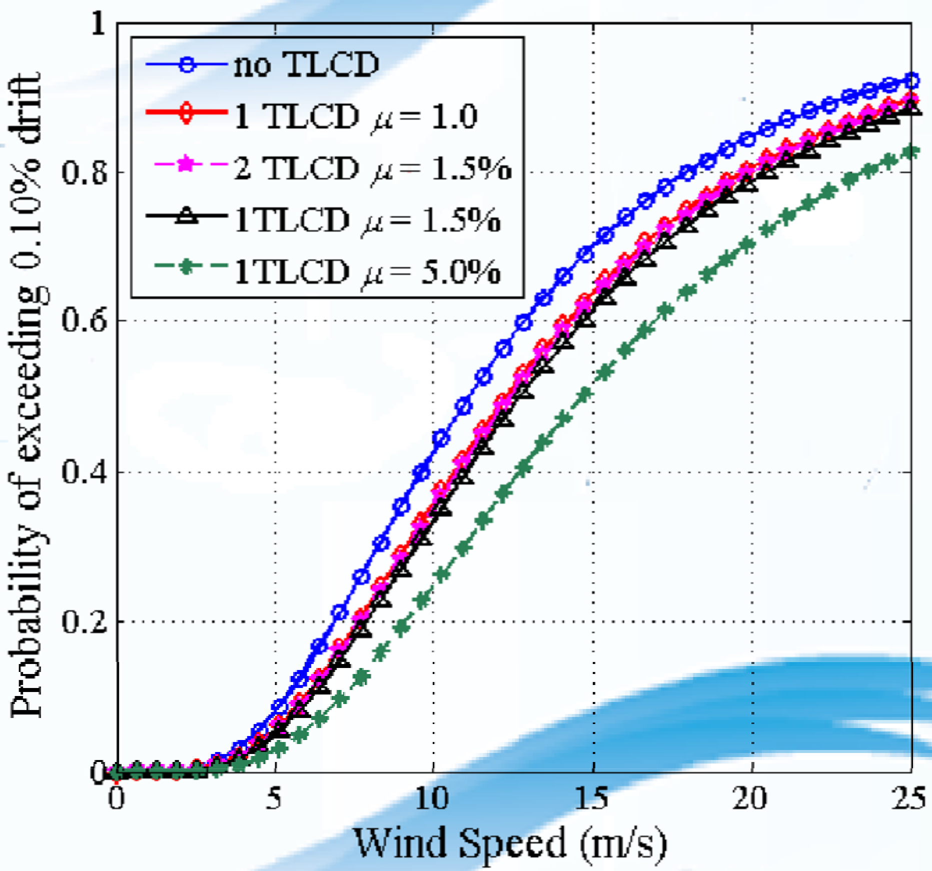
Minimization in displacements



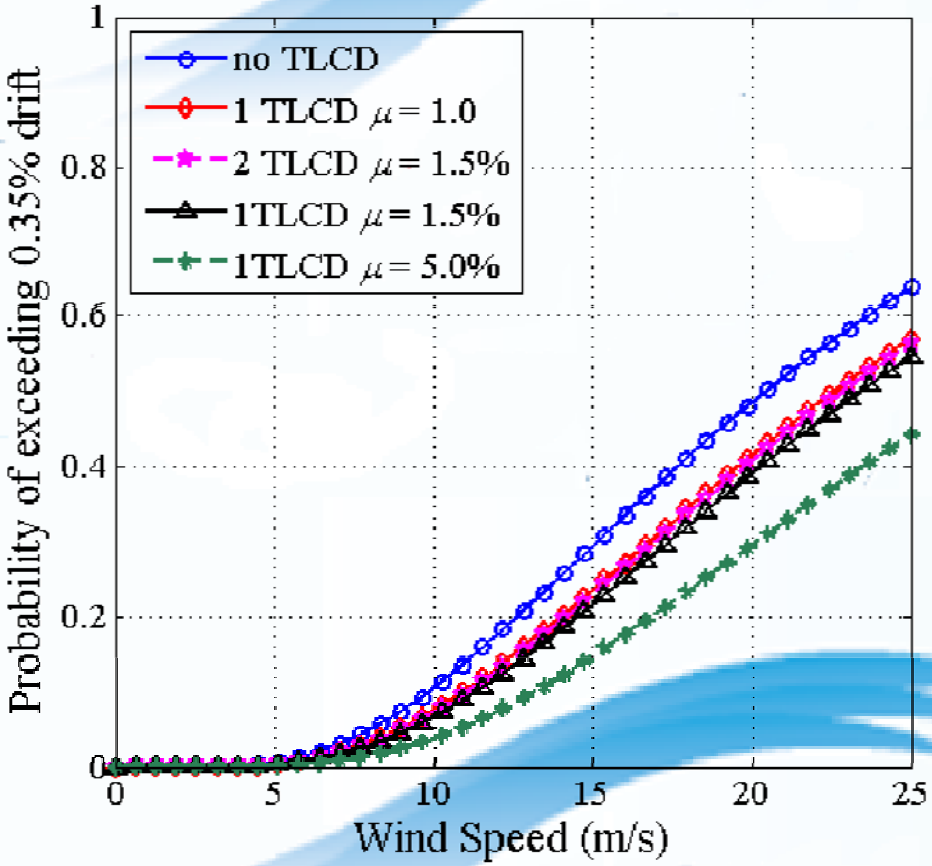
Minimization in displacements



Fragility Curves ~ Slight Damage



Fragility Curves – Yielding Initiation



Reliability Improvements

- Annual probabilities of exceeding predefined drift thresholds

$$P[D_w \geq D_{Ls}] = \int_0^\infty P[D_w \geq D_{Ls} \mid v_w] f(v_w) dv_w$$

Damage Level	West Texas		
	0.1%	0.25%	0.35%
No TLCD	0.322	0.211	0.176
One TLCD μ =1.0%	0.294 8.8%	0.187 11.1%	0.155 12.0%
Two TLCDs μ =1.5%	0.291 9.8%	0.184 12.5%	0.152 13.6%
One TLCD μ =1.5%	0.284 **11.7%**	0.179 **14.8%**	0.148 **16.0%**
One TLCD μ =5.0%	0.247 **23.4%**	0.150 **28.8%**	Negligible **-**

Conclusions

- TLCD significantly minimizes dynamic responses
- TLCD effectively reduces structural demands

  e.g. Shear Force and base moments

  - Low cost of materials and construction of foundations and towers.
- TLCD improves the reliability of multi-mega wind turbines
- For the same total damper mass, a single TLCD is more effective than multiple dampers

Future Work

- Quantify TLCD improvements to fatigue life of turbines
- Investigate TLCD use for offshore wind turbines

Other related research

- Analytical system reliability methods
  - Mensah, A. F., Duenas-Osorio, L., "A closed-form technique for the reliability and risk assessment of wind turbine systems", *Energies* **2012, 5, 1734-1750**
- Probability-based criteria for seismic load combination
  - Mensah, A. F., Duenas-Osorio, L., "Probabilistic combination of earthquake and operation loads for wind turbines", *15th World Conference on Earthquake Engineering (WCEE) in Lisbon, Portugal, September 24-28, 2012.*

Thank you

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