

格瑞士太阳能跟踪系统项目 GRACE SOLAR

风工程咨询 WIND ENGINEERING CONSULTATION

RWDI #2100531

January 21, 2021

接收方 SUBMITTED TO

厦门格瑞士太阳能科技有限公司
Xiamen Grace Solar Technology Co., LTD

提交方 SUBMITTED BY

Yan Jiang, M.A.Sc., P.Eng.
Project Engineer
Yan.Jiang@rwdi.com

钱峰, 高级工程师, 项目总监
Senior Engineer, Senior Project Manager
Feng.qian@rwdi.com

Matthew T. L. Browne, M.Eng., P.Eng., M.ASCE
Project Manager / Technical Director / Principal
Matthew.Browne@rwdi.com

杜向东博士, 注册工程师, 技术总监 Xiangdong Du, Ph.D., P.Eng.
Principal, Director of RWDI China Inc.
Xiangdong.Du@rwdi.com

安邸建筑环境工程咨询(上海)有限公司
RWDI International China Inc.
上海市浦东新区南泉北路 429 号
T: 021-80284316



摘要 EXECUTIVE SUMMARY

RWDI 受厦门市格瑞士太阳能科技有限公司委托，提供与其地面安装单轴追踪器相关的风工程咨询服务。

RWDI was retained by Xiamen GRACE SOLAR Technology Co., Ltd. to provide wind engineering consulting services related to its Ground Mounted Single-Axis Tracker System.

要点 Key points

- 风洞试验步骤满足或超过 ASCE 7, ASCE 49-12 规范要求。

The wind tunnel test procedures met or exceeded the requirements set out in the ASCE 7, and ASCE 49-12.

- 风荷载表示为与 ASCE 7 中概述的方法兼容的系数。

The wind loading is presented as coefficients to be compatible with the approaches outlined in ASCE 7.

- 表 1 给出了建议的静态风荷载系数。

The recommended static wind loading coefficients are provided in Table 1.

- 图 3 至 10 给出了建议的动态（惯性）风荷载系数。

The recommended dynamic (inertial) wind loading coefficients are provided in Figures 3 to 10.

- The zoning plan for various average areas is shown in Figure 2.

- 跟踪器系统适用性范围见 3.3.2 节。

Tracker system applicability tolerances are presented in Section 3.3.2.

- 本报告中的建议风荷载不包括任何安全系数。

The wind loading recommendations in this report do not include any factor of safety.

- 考虑动态/惯性荷载并未消除给定装置发生空气动力学不稳定性的可能（如第 2.2.2 和 2.2.3 节所述），也未充分预测来自气动弹性效应的自振力。为了降低系统遇到这些类型的不稳定性和气动弹性效应的风险，格瑞士太阳能追踪器需要把所有不大于设计风速情形下的扭转峰值限制在不超过 $\pm 5^\circ$ 。但是，满足此阈值并不能消除由于过度运动而导致系统破坏的风险。

The inclusion of dynamic/inertial loading does not eliminate the potential of aerodynamic instability (as discussed in Sections 2.2.2 & 2.2.3) occurring for a given installation, nor adequately predicts the self-excited forces from aeroelastic effects. **To reduce the risk of the system experiencing these types of instability and aeroelastic effects, GRACE SOLAR needs to constrain the peak rotations to not exceed $\pm 5^\circ$ for all wind speeds up to and including the design wind event. Meeting this threshold, however, does not eliminate the risk of failure due to excessive motions.**

目录 TABLE OF CONTENTS

摘要 EXECUTIVE SUMMARY

1	简介 INTRODUCTION	1
1.1	公司简介 Company Profile	1
1.2	项目描述 Project Description	3
1.3	目的 Objectives	3
2	背景和方法 BACKGROUND AND APPROACH	3
2.1	研究方法 Methodology	3
2.1.1	参考缩尺模型 Reference Scale Models	3
2.1.2	上风向地貌模拟 Simulation of Upwind Terrain	4
2.1.3	数据采集 Data Acquisition	5
2.1.4	从风洞试验结果确定设计风压 Determination Design Wind Pressures from Wind Tunnel Test Results	5
2.1.5	确定峰值风荷载 Determination of Peak Wind Loads	7
2.2	阵列动力分析 Array Dynamics	7
2.2.1	共振振动（机制#1） Resonant Vibration (Mechanism #1)	8
2.2.2	扭转颤振（机制#2） Torsional Flutter (Mechanism #2)	11
2.2.3	扭转驰振（机制#3） Torsional Galloping (Mechanism #3)	12
3	结果与讨论 RESULTS AND DISCUSSION	12
3.1	基底力和力矩系数 Force and Moment Coefficients	12
3.2	建议的风荷载系数 Recommended Wind Load Coefficients	13
3.2.1	静态风荷载系数 Static Wind Load Coefficients	13
3.2.2	动态风荷载系数 Dynamic Wind Load Coefficients	14
3.2.3	风荷载的确定 Determination of Full-Scale Wind Loads	15
3.2.4	开放区域和大型障碍物的影响 Effect of Open Areas and Large Obstructions	15
3.2.5	步进阵列边缘 Stepped Array Edges	16
3.2.6	大型阵列分区的扩展 Extension of Large Array Zoning	16
3.2.7	抗风设计过程 Process for Wind Design	17
3.3	结果的适用性 Applicability of Results	18
3.3.1	风荷载建议的适用性 Applicability of Wind Load Recommendations	18
3.3.2	跟踪系统冗余范围 Tracker System Tolerances	19

附表 LIST OF TABLES

表 1:	静态风荷载系数
Table 1:	Static Wind Load Coefficients

附图 LIST OF FIGURES

图 1a-d:	风洞模型
图 2:	风荷载分区图
图 3:	动态风荷载系数 - 0° 倾角
图 4:	动态风荷载系数 - 5° 倾角
图 5:	动态风荷载系数 - 15° 倾角
图 6:	动态风荷载系数 - 15° 倾角特殊工况
图 7:	动态风荷载系数 - 20° 倾角
图 8:	动态风荷载系数 - 30° 倾角
图 9:	动态风荷载系数 - 45° 倾角
图 10:	动态风荷载系数 - 60° 倾角
Figure 1a-d:	Wind Tunnel Models
Figure 2:	Key Plan for Wind Loading
Figure 3:	Dynamic Wind Load Coefficients - 0° Tilt
Figure 4:	Dynamic Wind Load Coefficients - 5° Tilt
Figure 5:	Dynamic Wind Load Coefficients - 15° Tilt
Figure 6:	Dynamic Wind Load Coefficients - 15° Tilt Special Configuration
Figure 7:	Dynamic Wind Load Coefficients - 20° Tilt
Figure 8:	Dynamic Wind Load Coefficients - 30° Tilt
Figure 9:	Dynamic Wind Load Coefficients - 45° Tilt
Figure 10:	Dynamic Wind Load Coefficients - 60° Tilt

附录 LIST OF APPENDICES

附录 A:	抗风设计过程
Appendix A:	Process for Wind Design



1 简介 INTRODUCTION

厦门市格瑞士太阳能科技有限公司委托 Rowan Williams Davies & Irwin Inc. (RWDI) 提供与其地面安装单轴跟踪系统相关的风工程咨询服务。本报告介绍了项目目标，背景，方法，并讨论了 RWDI 评估的结果。摘要中提供了总体评估建议的摘要。

Rowan Williams Davies & Irwin Inc. (RWDI) was retained by GRACE SOLAR Technology Co., Ltd. to provide wind engineering consulting services related to its Ground Mounted Single-Axis Tracker System. This report presents the project objectives, background, approach, and provides a discussion of the results from RWDI's assessment. A summary of the overall recommendations from the assessment is presented in the Executive Summary.

1.1 公司简介 Company Profile

RWDI 通过结合创新思维、协作解决问题以及创造更大可能的动力，帮助客户应对建筑环境中的复杂挑战。在过去的四十年中，我们已经从一家在风工程领域拥有深厚技术专长的加拿大公司发展成为一家以解决在世界上建筑性能，气候工程和环境方面最苛刻的挑战而闻名的全球性公司。我们的团队由 500 多名工程师，科学家，可持续发展专家和支持团队组成，他们帮助世界各地的客户满足他们的工程需求并推进更广泛的业务目标。我们在北美，欧洲和亚太地区都有办事处。在不断创新的建筑和基础设施项目上取得成功 - 提高其绩效和效率，以及评估和减轻其对环境的影响。

RWDI helps clients tackle complex challenges in the built environment by combining innovative thinking, collaborative problem solving and a passion for expanding the boundaries of the possible. Over the past four decades, we've evolved from a respected Canadian company with deep technical expertise in wind engineering to a global firm known for solving some of the world's most demanding building performance, climate engineering and environmental challenges. Our team of more than 500 engineers, scientists, sustainability specialists and support professionals help clients around the world meet their engineering needs and advance their broader business goals. Working from offices across North America, Europe and the Asia-Pacific region, we drive success on ambitious building and infrastructure projects – enhancing their performance and efficiency as well as assessing and mitigating their environmental impacts.

作为超高层建筑风工程的全球领导者，根据高层建筑和城市居住委员会（CTBUH）的统计，RWDI 已成为世界上 10 座最高建筑中的 7 座，以及前 100 座高建筑中的近一半建筑的主要风工程顾问。我们的团队包括许多世界顶级的桥梁空气动力学专家，我们在风洞中测试了世界上一些最长跨度的桥梁。下表提供了 RWDI 曾为其提供服务的一些地标性建筑。

The world leader in wind engineering for skyscrapers, RWDI has been the principal wind consultant on seven of the world's 10 tallest buildings, and nearly half of the top 100, according to the Council on Tall Buildings and Urban Habitat (CTBUH). Our team includes many of the world's top bridge-aerodynamics experts, and we've tested some of the world's longest-span bridges in our wind tunnels. The following list provides a minuet selection of the landmark structures RWDI has contributed toward.



名称 NAME	高度/跨度 (米) HEIGHT/SPAN (m)	地点 LOCATION
吉达塔 Jeddah Tower	1,000	Jeddah, Saudi Arabia
迪拜塔 Burj Khalifa	828	Dubai, United Arab Emirates
上海中心 Shanghai Tower	632	Shanghai, China
墨西拿海峡大桥 (悬索) Messina Strait Bridge (Suspension)	3,300	Sicily to Calabria, Italy
金门大桥 (悬索) Golden Gate Bridge (Suspension)	1,280	San Francisco, CA, USA
昂船洲大桥 (斜拉桥) Stonecutters Bridge (Cable-Stayed)	1,020	Hong Kong, China

我们利用这一丰富的专业知识来预测其他类型结构的风效应，包括屋顶安装和地面安装的太阳能系统，帮助许多领先的制造商优化他们的设计。我们在桥梁空气动力学方面的专业知识基于数十年来使用最先进的截段模型技术得到的经验，并结合我们用于非线性 3D 颤振分析的专有工具来评估稳定性；以及时域中的理论抖振分析来预测风引起的响应。这种方法特别适合于检验基于单个位置驱动的中心扭矩管的太阳能跟踪系统。与大跨度桥梁一样，这些单轴跟踪器可以因为其横截面几何形状和结构动态特性（即频率和阻尼）而导致各种类型的扭转空气动力学不稳定性。这些不稳定性涉及扭矩管周围的旋转运动（扭转），一旦超过临界速度，扭矩管的扭转运动就会随风速不可控制地增长。有许多术语适用于这种类型的运动，包括：颤振，扭转驰振和扭转发散。应该注意的是，观察到的结构响应在每种情况下都是相似的，但潜在的空气动力学机制是不同的。使用准静态理论可以预测扭转发散和驰振；然而，仅通过静力和力矩系数的知识无法预测颤振。因此，我们建议任何空气动力学不稳定性研究都应该用空气动力学导数来描述作用在结构上的自激空气动力。我们推荐这种方法，因为空气动力学导数可用于预测任何这些观察到的扭转空气动力学不稳定性的发生，而静态测量仅提供观察到的现象的部分描述。

We tap this vast expertise to predict wind effects on other types of structures, including roof-mounted and ground-mounted solar energy systems, helping many leading manufacturers optimize their designs. Our expertise in bridge aerodynamics is based on decades of using state-of-the-art sectional model techniques, combined with our proprietary tools for nonlinear 3D flutter analysis to assess stability and theoretical buffeting analyses in the time domain to predict wind-induced responses. This approach is especially well-suited to examine solar tracking systems relying on a central torque tube driven from a single location. Like long-span bridges, these single-axis trackers can be prone to various types of torsional aerodynamic instabilities depending on their cross-sectional geometry and structural dynamic properties (i.e., frequencies and damping). These instabilities involve rotational motions (torsion) about the torque tube that grow uncontrollably with wind speed once a critical speed is surpassed. There are many terms applied to this type of motion including: flutter, torsional galloping and torsional divergence. It should be noted that the observed response of the structure is similar in each case, but the underlying aerodynamics are distinct. Torsional divergence and galloping can be predicted using quasi-static theory; however, flutter cannot be predicted through knowledge of the static force and moment coefficients alone. Therefore, it is our recommendation that any study of aerodynamic instability employ the use of aerodynamic derivatives to describe the self-excited aerodynamic forces acting on the structure. We recommend this approach since



aerodynamic derivatives can be used to predict the occurrence of any of these observed torsional aerodynamic instabilities, while static measurements only offer a partial description of the observed phenomena.

1.2 项目描述 Project Description

典型的格瑞士单轴太阳能跟踪器的每排长约 95 米，宽 2.35 米（弦长），由 84 个纵向模块和中间驱动系统组成。每个模块条直接连接到主轴，该管轴高于地面约 1.6 米并由间隔在 6.5 米至 8 米之间的 13 个支柱支撑。典型的中心到中心行间距为 5.9 米（东西方向），代表 0.4 的地面覆盖率（GCR）。

Each row in the typical GRACE SOLAR Single-Axis Solar Tracker is approximately 95 m long and 2.35 m wide (chord length), comprised of 84 portrait modules with a middle drive system. Each strip of modules is directly attached to a tube, which is typically 1.6 m above grade and supported by thirteen posts spaced between 6.5 m to 8 m apart. The typical center-to-center row spacing is 5.9 m (east-west direction), representing a ground cover ratio (GCR) of 0.4.

1.3 目的 Objectives

RWDI 的主要任务是使用刚性压力模型，通过风洞测试，来推荐作用于系统各部件的静态和动态风荷载。研究目的是推荐与 ASCE 7 要求一致的风荷载系数。

The primary objective of RWDI's commission was to recommend the static and dynamic wind loads acting on various components of the system based on wind tunnel testing using a rigid pressure model. The intent was to recommend wind load coefficients consistent with the ASCE 7.

2 背景和方法 BACKGROUND AND APPROACH

2.1 研究方法 Methodology

2.1.1 参考缩尺模型 Reference Scale Models

为了获得详细的风荷载系数，以 1:45 的比例制作格瑞士跟踪系统的缩尺模型，并在安大略省圭尔夫的 RWDI 边界层风洞中对 8 个 PV 行的通用阵列进行了测试。该模型基于 2020 年 10 月 13 日收到的图纸，倾角可在 0° 至 ±60°（从水平算起）范围内调整，对中心距为 5.9 m 的 0°，5°，15°，20°，30°，45° 和 60° 倾角以及一个应格瑞士要求的 15° 倾角的特别工况进行了测试。每排长度 95 米，并在 21 个截面位置进行测量。图 1a 至 1d 给出了所选倾角的边界层风洞中的缩尺模型的照片。

To obtain detailed wind load coefficients a scale model of the GRACE SOLAR Tracker System was constructed at a 1:45 scale, for testing in RWDI's boundary layer wind tunnel facility in Guelph, Ontario, for a generic array of eight PV rows. The model was based on drawings received on October 13, 2020, and the tilt angle was adjustable within the range of 0° through ±60° (from horizontal), with 0°, 5°, 15°, 20°, 30°, 45° and 60° selected for testing at a center-

to-center row spacing of 5.9 m. As requested by GRACE SOLAR, a special configuration for 15° tilt angle was also tested. Each row was 95 m long and instrumented at 21 discrete locations. Photographs of the scale model in the boundary layer wind tunnel are shown for selected tilt angles in Figures 1a through 1d.

拟议系统的基本几何形状和尺寸如图 2 所示，其中还提供了其中一排的传感器（测压点）位置。测量脉动风压的测压点安装在太阳能板的顶部和底部表面的许多位置。通过使用快速成型技术在固体模型中嵌入内部压力通道来安装测压点，使它们不会干扰气流。然后，这些“生长的”管道终止于模型底部下方，橡胶管将压力传递给扫描系统。

The basic geometry and dimensions of the proposed system are shown in Figure 2, which also provides the sensor (tap) locations for a typical row. Taps that measure fluctuating wind pressure were installed on the top and bottom surfaces of the panels at numerous locations. Particular attention was given to the installation of the pressure taps so that they did not interfere with the wind flows, and this was achieved by imbedding interior pressure passages in the solid model using rapid-prototyping technology. These “grown” passages then terminated underneath the base of the model, where rubber tubes transmitted the pressures to the scanning system.

2.1.2 上风向地貌模拟 Simulation of Upwind Terrain

对场地模型以外的大气边界层上风向地貌影响是通过在风洞工作段前方设置适当的湍流尖塔与地面粗糙元对每个风向逐一模拟。这一风洞模拟以及随后的模型数据分析用来反映所有风向下的开阔地貌（ASCE 7 中定义的地貌类别 C）。这些风场（开阔地貌）代表了最可能出现的项目现场的地貌类别。其中风向定义为风的来流方向，以正北向为零度顺时针计算。

Beyond the modeled area, the influence of the upwind terrain on the planetary boundary layer was simulated in the testing by appropriate roughness on the wind tunnel floor and flow conditioning spires at the upwind end of the working section for each wind direction. This simulation, and subsequent analysis of the data from the model, was targeted to represent generic open terrain conditions (Exposure C as defined in ASCE 7) for all wind directions. These flow conditions (Open Terrain) represent the most likely exposure for full-scale installations. Wind direction is defined as the direction from which the wind blows, measured clockwise from true north.

大多数国际规范/标准（包括 ASCE 7）都给出了项目位置的适当的地貌类别的建议。一般而言，适用的地形粗糙度应在上风向上持续至少 50 米。不同地貌类别的风荷载可以从本报告中提供的系数和使用地貌修正系数（例如 ASCE 7 的 K_z ）确定。在大型阵列的场内（距离边界至少 50 米）的地貌类别可以被视为开阔地貌。

Guidance for selecting an appropriate exposure category for a particular installation is given in most international codes/standards, including the ASCE 7 Standard. In general, the applicable terrain roughness should persist in the upwind direction for at least 50 m. The wind loading for different exposures can be determined from the coefficients presented in this report and the use of an exposure factor, such as K_z in the ASCE 7. The exposure within the field of a large array (at least 50 m away from the perimeter) may be taken as open terrain.

2.1.3 数据采集 Data Acquisition

使用能够响应短压力脉动的系统在每个测压点处测量平均压力，压力脉动的均方根，峰值负压和峰值正压。由于对称性，测量了间隔 10° 的 19 个风向。基于在风洞中测试模型中心上方 1.5 米高处测量的平均动态压力，将测量数据转换为压力系数。记录并保存了所有测压点处的瞬时压力脉动的时程数据以用于测试后分析。

The mean pressure, the root-mean-square of pressure fluctuations and the peak negative and peak positive pressures were measured at each tap using a system capable of responding to short pressure fluctuations. Due to symmetry, measurements were taken for 19 wind directions spaced 10° apart. The measured data were converted into pressure coefficients based on the mean dynamic pressure measured at a height of 1.5 m in the wind tunnel, directly above the center of the test model. Time histories of the instantaneous pressure fluctuations at all tap locations were recorded and saved for post-test analysis.

2.1.4 从风洞试验结果确定设计风压 Determination Design Wind Pressures from Wind Tunnel Test Results

对于太阳能光伏阵列的设计，必须考虑在适当的 PV 元件上作用的净风压。本报告中提供的结果包括作用在 PV 模块上表面和下表面上的风压。通过直接测量元件上的瞬时面积加权压差来确定作用在每个阵列元件上的净压力。

For design of solar arrays, the net wind pressure acting across an appropriate PV element must be considered. The results provided in this report include the contributions of the wind pressures acting on both the upper and lower surfaces of the PV modules. The net pressure acting on each array element was determined by directly measuring the instantaneous area-weighted pressure difference across the element.

影响任何结构的风压模式随空间和时间变化并且非常复杂。在结构的任何一个构件中产生的力或应力在某种程度上取决于结构的互连单元上的连续变化的压力模式。对于特定结构单元的设计，相关的风荷载是在单元上的子区域上同时作用的那些风荷载。例如，假设所研究的荷载工况之一是导致该部分上最高的总体上吸力的工况。

The wind pressure patterns affecting any structure vary both spatially and with time and are very complex. The force or stress generated in any one component of the structure depends to some extent on the continually changing pressure pattern over the interconnected elements of the structure. For the design of a particular structural element, the relevant wind loads are those acting simultaneously over the element's tributary area. For example, assume one loading condition of interest to be that which causes the highest overall upward force on a section.

在这种情况下，为了确定向上的力 L，需要确定最高瞬时值

In this case, to determine the upward force, L, one would need to determine the highest instantaneous value of

$$L = p_1 A_{1p} + p_2 A_{2p} + p_3 A_{3p} + \dots$$

其中 p_1 , p_2 , p_3 等是在代表性测压点 1,2,3 等处测量的瞬时压力， A_{1p} , A_{2p} , A_{3p} 等是与每个测压点相关的子区域。上述总和中的每个项是来自其中一个区域的法向力。由于该区域的风压缺乏相关性，单个项不在同一时刻达到峰值。因此，为了



确定真正的峰值向上力，重要的是在连续和瞬时的基础上进行上述求和。结果通常以系数形式表示。例如，在上吸力的情况下，力除以参考风压 q_z 和子面积 A ，以获得

where p_1, p_2, p_3 , etc. are the instantaneous pressures measured at representative pressure taps 1, 2, 3, etc. and A_{1p}, A_{2p}, A_{3p} , etc. are the tributary areas associated with each of the pressure taps. Each term in the above summation is the contribution to the normal force coming from one of the areas. Because of lack of correlation of the wind pressures over the area, the individual terms do not all reach their peak at the same instant in time. Therefore, to determine the true peak upward force, it is important to carry out the above summation on a continuous and instantaneous basis. The results are usually expressed in coefficient form. For example, in the case of the upward force, the force is divided by the reference wind pressure, q_z , and the tributary area, A , to obtain

$$\frac{L}{q_z A} = \frac{1}{q_z} \left(\frac{p_1 A_{1p}}{A} + \frac{p_2 A_{2p}}{A} + \frac{p_3 A_{3p}}{A} + \dots \right)$$

右侧括号中的总和是从风洞测试中获得的瞬时压力，是总的向上力除以表面积，因此是面积平均压力。

The summation in the brackets on the right-hand side, obtained on an instantaneous basis from the wind tunnel, is the overall upward force divided by the surface area and so is an area-averaged pressure.

上述讨论代表了一种压力模式。由于对结构分析每种可能发生的风压模式是不切实际的，因此有必要从风洞结果中选择某些主导的荷载工况，这些工况可能以重要方式对结构施加压力（如同通过建筑规范来以简化的方式有效地完成）。

The above discussion represents one pressure pattern. Since it is impractical to analyze the structure for every possible wind pressure pattern that might occur, it is necessary to select from the wind tunnel results certain loading scenarios that tend to be dominant and that are likely to stress the structure in important ways (as is effectively done by building codes in a simplified manner).

在这项研究中，根据与格瑞士太阳能的讨论以及 RWDI 在类似结构方面的经验，研究了各种不同的荷载工况。关注的主要荷载工况是

- 各种节段长度的垂直于表面的风荷载（上吸力和下压力）；
- 各种节段长度上扭矩管的力矩（扭转）荷载。

In this study, various wind loading scenarios were investigated based on discussions with GRACE SOLAR, as well as RWDI's experience with similar structures. The primary loading scenarios of concern were

- normal-to-surface wind loading (uplift and downforce) for various tributary lengths;
- moment (torsional) loading about the torque tube for various tributary lengths.

2.1.5 确定峰值风荷载 Determination of Peak Wind Loads

上一节中描述的各个荷载效应的时间序列分为 N 个子间隔，并且每个子间隔的最大值和最小值都有所记录。每个子间隔的持续时间设置得足够长，以使相邻间隔中的峰值压力不太可能相关，因此可以将其视为独立事件。

The time series of each load effect described in the previous section is divided into N sub-intervals, and the maximum and minimum values for each sub-interval are recorded. The duration of each sub-interval is set long enough that the peak pressures in adjacent intervals are unlikely to be correlated and thus can be treated as independent events.

通过以下 Fisher-Tippet I 型分布的表达式，可以确定子间隔最大值和最小值中的最大和最小压力系数：

The determination of the maximum and minimum pressure coefficients from the sub-interval maxima and minima can be carried out by using a Fisher-Tippet type I distribution, which is of the form:

$$P(C) = \exp(-\exp[-a(C - u)])$$

将此表达式与子间隔数据的最大值和最小值拟合，可以确定 a 和 u 的值。在该表达式中， $P(C)$ 是峰值压力系数 C 的概率分布， $1/a$ 和 u 分别是分布的方差和众数。通过以下公式可以确定整个采样期间的最大压力系数：

The values of a and u are determined by fitting this expression to the sub-interval data on maxima and minima. In this expression, $P(C)$ is the probability distribution of the peak pressure coefficient C , and $1/a$ and u are respectively the dispersion and mode of the distribution. The maximum pressure coefficient for the whole sample period can be then determined from:

$$C_{\hat{p}} = u + \frac{(1.5 + \ln N)}{a}$$

其中 N = 子间隔数。

where N = number of sub-intervals.

可以使用相同的方法来获得最小压力系数的大小。 $(1.5 + \ln N)/a$ 项中的 1.5 是根据对预期峰值压力的深入分析得出的，其中考虑了风速和压力系数的典型联合概率分布（参见 Irwin¹），通常得出峰值压力系数略高于测试中实际记录的最大值。这种确定 $C_{\hat{p}}$ 的方法优于简单地使用最大记录压力，因为它避免了使用单个数据点所产生的统计分散问题。

The same method can be used to obtain the magnitude of the minimum pressure coefficient. The value 1.5 in the term $(1.5 + \ln N)/a$ is derived from an in-depth analysis of the expected peak pressure taking into account the typical joint probability distributions for the wind speed and pressure coefficient (see Irwin¹) and generally results in a slightly higher peak pressure coefficient than the maximum actually recorded in the tests. This method of determining $C_{\hat{p}}$ is superior to simply using the maximum recorded pressure since it avoids the statistical scatter associated with using a single data point.

2.2 阵列动力分析 Array Dynamics

¹ Irwin, P.A., Pressure Model techniques for Cladding Loads, Journal of Wind Engineering and Industrial Aerodynamics, 29 (1988) 69-78.



通过考虑空气动力学重要风向的平均和脉动风荷载来确定结构风荷载分布。风荷载的脉动部分是由于风湍流（抖振）和结构的动态响应（共振）。对于更灵活和轻微阻尼的结构，由于共振而产生的惯性荷载可以对脉动的风荷载作出显著贡献。迄今为止，RWDI 已经认识到风引起太阳能装置部分振动或不稳定的三种机制：

The structural wind load distributions were determined by considering the mean and fluctuating wind loading for aerodynamically important wind directions. The fluctuating portion of the wind loads is due to wind turbulence (buffeting) and the dynamic response of the structure (resonant vibration). For more flexible and lightly damped structures, the inertial loads due to resonant vibration can add a significant contribution to the fluctuating wind loads. To date RWDI has become aware of three mechanisms for wind to cause vibration or instability of portions of a solar installation:

1. 共振振动由一般的风抖振或跟踪器场地上风位置的阵列产生的湍流而引起的尾流共振效应导致。
Resonant Vibration is caused by either general wind buffeting or the wake resonance effect caused by the turbulence generated from the upwind rows of a tracker field.

2. 扭转颤振是一种自激气动失稳，其中气动力取决于结构本身的旋转和角速度，它可以导致扭转运动或耦合的扭转和垂直运动的很大振幅。对于依赖于从单个位置驱动的中央扭矩管的跟踪器，扭转振动模式是由通常在行末端开始的颤振而引起的。

Torsional Flutter is a self-excited aerodynamic instability in which the aerodynamic forces depend on the rotation and angular velocity of the structure itself, and it can lead to very large amplitudes in torsional motion or coupled torsional and vertical motion. For trackers relying on a central torque tube driven from a single location, a twisting mode of vibration is created by a form of flutter generally initiated at the ends of the row.

3. 扭转驰振是一种不稳定性，它取决于结构的旋转，由于气动俯仰力矩的变化，会导致结构产生较大的响应。开始时，增加的俯仰力矩会降低整体结构刚度，导致结构单向扭转或根据结构的剩余刚度而产生的振荡运动。随着风速的增加，一旦超过结构阻力，这种不稳定性很可能会导致系统不工作。

Torsional Galloping is an instability that depends on the rotation of the structure and can lead to large responses in the structure due to variations in the aerodynamic pitching moment. At its onset, the increasing pitching moment reduces the overall structural stiffness, resulting in either unidirectional twisting of the structure or oscillatory motion depending on the remaining stiffness of the structure. As the wind speed is increased it is likely that this instability will lead to failure once the structural resistance is surpassed.

2.2.1 共振振动（机制#1） Resonant Vibration (Mechanism #1)

对于机制 1，由于与上风行涡旋脱落有关的窄带频率上的能量增加，导致下风跟踪器的动态抖振响应增加。静态压力数据中的动态放大因子包含了这种类型的激振增加。因此，发生这种情况的可能性取决于结构系统的振动的固有频率，风速，弦长以及系统中的阻尼。

With regard to Mechanism #1, increased dynamic buffeting response of downwind trackers occurs due to the increased energy over narrow-banded frequencies related to shedding of vortices from upwind rows. This type of



increased excitation is captured by the dynamic amplification factors in the static pressure data. The likelihood of this occurring is therefore dependent on the natural frequency of vibration of the structural system, wind speed, chord length, as well as the damping in the system.

光伏阵列在其使用寿命期间将经受各种强度的风速。在强风情况下，阵列内的结构部件将在结构的寿命期间经受重复荷载并且会受到疲劳影响。随着风速变化，荷载的重复次数和幅度也会变化。这意味着在整个设计寿命期间，阵列将经历多个不同大小的重复的荷载。因此，在设计过程中对于对应于特定回归期和特定寿命的结构部件的设计，必须考虑这种风速脉动。

The array will be exposed to wind speeds of various intensities during its lifetime. During strong wind events, structural components within the array will be subjected to repetitive loads during the life of the structure and may be subject to fatigue. As the wind speed varies, the number and magnitude of cycles present in the loading will vary as well. This implies that over the design life, the array will be subjected to a number of cycles of different magnitudes. Therefore, for the design of structural components corresponding to a particular return period and specific lifetime, such fluctuations in wind speed have to be taken into account during the design process.

在评估疲劳时，重要的是获得适当的 S-N 曲线（即疲劳应力曲线，或强度，极限与循环次数），具体取决于用于制造结构和连接系统的材料的性能。来自 S-N 曲线的一个重要参数是材料的耐久极限，其表示应力水平，低于该应力水平，疲劳不是问题，因此允许无限次数的荷载的重复。为了对此进行评估，所提供的风荷载（静态+动态）应以与建筑规范方法计算的风荷载相同的方式应用于系统，并且把支撑结构和连接中产生的应力与材料的耐久极限相比。如果估计的应力低于材料的耐久极限，则无论多少次的荷载重复，都不会出现疲劳失效的可能性。但是，如果最大应力水平高于材料的耐久极限，则在一定次数的荷载重复之后可能出现疲劳失效。值得注意的是，这种方法假设位移很小及气动弹性效应可以忽略不计。使用所提供的风荷载来评估支撑结构和连接结构的疲劳是保守的，因此如果得到的分析应力表明设计中可能存在与疲劳相关的问题，则可以委托 RWDI 提供用于评估结构系统的荷载重复。

In assessing fatigue, it is important to obtain the appropriate S - N curve, (i.e. curve of fatigue stress, or strength, limit versus number of cycles), depending on the properties of the material used for the construction of the structural system and connections. One important parameter from the S - N curve is the endurance limit of the material, which represents a stress level below which fatigue is not an issue and therefore an infinite number of load cycles are permitted. To evaluate this, the provided wind loads (static + dynamic) should be applied to the system in the same manner as would wind loads calculated by building code methods and the resulting stresses in the support structure and connection compared to the endurance limit of the material. If the estimated stresses are comfortably below the endurance limit of the material, there is no chance of fatigue failure regardless of the number of loading cycles. However, if the maximum stress levels are above the endurance limit of the material, fatigue failure may be an issue if a sufficient number of cycles occur. It is important to note that this approach assumes that the displacements are small and aeroelastic effects are negligible. The use of the provided wind loads to evaluate fatigue of the support structure and connections is conservative, and therefore if the resulting analysis stresses indicate there may be fatigue related issues in the design, RWDI may be retained to provide fatigue cycles for the evaluation of the structural system.

由于这些动态影响而导致的荷载放大可通过基于风荷载测得的功率谱和结构振动的固有频率的动态放大系数来近似囊括。动态放大系数 DAF 定义为

The load amplification due to these dynamic effects can be approximately accounted for by dynamic amplification factors based on the measured power spectra of the wind loading and the natural frequencies of vibration of the structure. The dynamic amplification factor, DAF, is defined as

$$DAF = \sqrt{1 + \frac{\pi}{4\zeta} \frac{fS(f)}{\sigma^2}}$$

其中 f = 固有频率 (Hz) ;

ζ = 阻尼比, 是临界值的一部分;

$\frac{fS(f)}{\sigma^2}$ = 固有频率 (f) 处的归一化频谱密度。

where f = natural frequency (Hz);

ζ = damping ratio, as a fraction of critical;

$\frac{fS(f)}{\sigma^2}$ = normalized spectral density at the natural frequency (f).

包括 DAF 在内的总峰值荷载可以使用以下表达式概括地描述, 该表达式包括平均值, 背景 (“B”) 和共振 (“R”) 分量。

The total peak loading, including the DAF, can be described in general terms using the following expression which includes the mean, background (“B”), and resonant (“R”) components.

$$P_{total} = P_{mean} \pm P_{rms} \cdot \sqrt{(g_{Bp})^2 + (g_{Rp})^2 \cdot (DAF^2 - 1)}$$

对于大型民用建筑 (例如高层建筑), 背景峰值因子 g_{Bp} 通常为 3.5 到 4.0, 但对于较小的结构 (如太阳能跟踪器) 则可能更高。可以在 Davenport 中找到用于估算共振峰值因子 g_{Rp} 的常用表达式, 该表达式很接近高斯概率分布:

The background peak factor, g_{Bp} , is typically 3.5 to 4.0 for large civil structures (e.g., tall buildings), but can be higher for smaller structures like solar trackers. A commonly-used expression for estimating the resonant peak factor, g_{Rp} , can be found in Davenport² for a response that has a closely Gaussian probability distribution:

$$g_R = \sqrt{2\ln(vT)} + \frac{0.577}{\sqrt{2\ln(vT)}}$$

² Davenport, A.G. (1964) Note on the distribution of the largest value of random function with application to gust loading, Proceedings of the Institution of Civil Engineers, 28, 187–196.



其中， v 是循环频率，通常将其保守地视为自然频率； T 是需要最大值的时间间隔，通常为 3600 秒（即 1 小时）。将时间间隔设为 3600 秒时，对于 0.5 Hz 至 5 Hz 之间的固有频率，此表达式得出的值在 4.0 到 4.5 的范围内，通常低于背景峰值因子。

where v is the cycling rate, often conservatively taken as the natural frequency; T is the time interval over which the maximum value is required, usually taken as 3600 seconds (1 hour). This expression yields values in the range of 4.0 to 4.5 for natural frequencies between 0.5 Hz and 5 Hz, when the time interval is taken as 3600 seconds, which are generally lower than the background peak factors.

值得注意的是，本报告中的系数是基于使用刚性模型的风洞测试，因此，不包括表现为自激力的流固耦合效应（或气动弹性效应）。如果跟踪器的扭转峰值超过 $\pm 5^\circ$ ，则在此提出的风荷载将不再有效，并且可能需要使用气动弹性模型进行进一步研究。但是，达到此阈值并不能消除由于过度运动而导致破坏的风险。

It is important to note that the coefficients in this report are based on wind tunnel testing using a rigid model, and therefore, do not include fluid-structure interaction effects (or aeroelastic effects) that manifest as self-excited forces. If the peak rotation of the tracker exceeds $\pm 5^\circ$ then the wind loading presented herein will no longer be valid, and further research using an aeroelastic model may be necessary. Meeting this threshold, however, does not eliminate the risk of failure due to excessive motions.

2.2.2 扭转颤振（机制#2）Torsional Flutter (Mechanism #2)

在某些情况下，可以看到在诸如太阳能电池板阵列的平板结构上发生空气动力学不稳定性。这种被称为不稳定性的运动一旦启动，就会不断增加直到系统失效或直到风速降低。因此颤振是必须避免的。颤振是一种自激的空气动力学不稳定性，其中空气动力取决于结构本身的旋转和角速度，并且它可以导致扭转运动或耦合的扭转和垂直运动中的非常大的振幅。扭转颤振表征高倾角行为。通常采取改变空气动力学形状，结构刚度或阻尼的方式来确保在预期的风速下不会出现颤振。但是，扭转峰值应限制在小于 $\pm 5^\circ$ ，以尽量减少颤振的风险。然而达到此阈值并不能消除由于过度运动而导致破坏的风险。

Aerodynamic instabilities are seen to occur in some circumstances on flat plate structures such as solar panel arrays. The class of motion referred to as an instability is where, once initiated, the motion increases until failure or until the wind speed is reduced. Flutter therefore must be avoided. Flutter is a self-excited aerodynamic instability in which the aerodynamic forces depend on the rotation and angular velocity of the structure itself, and it can lead to very large amplitudes in torsional motion or coupled torsional and vertical motion. Torsional Flutter characterizes high tilt angle behavior. Changes in aerodynamic shape, structural stiffness or damping are usually employed to ensure that flutter is not experienced at expected wind speeds. **However, the peak rotation should be constrained to less than $\pm 5^\circ$ to minimize the risk of flutter. Meeting this threshold, however, does not eliminate the risk of failure due to excessive motions.**



2.2.3 扭转驰振（机制#3）Torsional Galloping (Mechanism #3)

这种不稳定性取决于结构的旋转，并且由于空气动力俯仰力矩的变化可能导致结构中的巨大响应。在其开始时，增加的俯仰力矩降低了整体结构刚度，取决于结构的剩余刚度，将导致结构的单向扭转或振荡运动。随着风速增加，一旦超过其阻力，这种不稳定性可能会导致破坏。这种不稳定性被称为“扭转驰振”，表征低倾角行为。为了确保不发生破坏，应避免这些类型的不稳定性。改变空气动力学形状或结构刚度是可用的常用补救措施，以确保在预期风速下不会出现扭转发散。但是，扭转峰值应限制在小于 $\pm 5^\circ$ ，以最大限度地降低扭转发散的风险。然而达到此阈值并不能消除由于过度运动而导致破坏的风险。

This instability depends on the rotation of the structure and can lead to large responses in the structure due to variations in the aerodynamic pitching moment. At its onset, the increasing pitching moment reduces the overall structural stiffness, resulting in either unidirectional twisting of the structure or oscillatory motion depending on the remaining stiffness of the structure. As the wind speed is increased it is likely that this instability will lead to failure once their resistance is surpassed. This instability is referred to as “Torsional Galloping”, which characterizes low tilt angle behavior. To ensure failure does not occur, these types of instabilities should be avoided. Aerodynamic shape changes or structural stiffness are the usual remedial measures available to ensure that torsional divergence is not experienced at expected wind speeds. **However, the peak rotation should be constrained to less than $\pm 5^\circ$ to minimize the risk of torsional divergence. Meeting this threshold, however, does not eliminate the risk of failure due to excessive motions.**

3 结果与讨论 RESULTS AND DISCUSSION

本报告中的风荷载系数不包含安全系数或荷载系数，所给出的风荷载可等同于由规范计算所得风荷载，应用于光伏阵列。因此，建议为了设计目的，应根据对管辖区建筑的官方要求来应用适当的荷载系数。所有设计信息均以系数形式呈现，如下一节中所定义。

The wind load coefficients in this report do not contain safety or load factors and are to be applied to the PV arrays in the same manner as would wind loads calculated by code analytical methods. Hence it is suggested that appropriate load factors as required by the building official of jurisdiction should be applied to the wind pressures for design purposes. All design information is presented in coefficient form as defined in the next section.

3.1 基底力和力矩系数 Force and Moment Coefficients

风洞数据表示为与 ASCE 7 规范中定义的压力或力矩系数一致的压力或力矩系数。这些系数的定义如下。

The wind tunnel data were presented as pressure or moment coefficients consistent with those defined in the ASCE 7 Standard. The definitions of these coefficients are given below.

$$C_P = \frac{P_{net}}{\frac{1}{2} \cdot \rho \cdot U^2 \cdot K_{z_ASCE}}, \quad C_M = \frac{M_{torque}}{\frac{1}{2} \cdot \rho \cdot U^2 \cdot K_{z_ASCE} \cdot A \cdot L}$$

此处,

P_{net} , M_{torque} 是净压力 (垂直于 PV 模块的顶面) 和扭矩管的力矩;

ρ 是空气密度;

U 是开阔地貌 10 米高度处的 3 秒阵风风速;

根据 ASCE 7, K_{z_ASCE} 是开阔地貌上跟踪器高度 (H) 处的地貌修正系数 0.85;

A 是条、柱、四分之一行, 半行或全行的面积 (见图 2);

L 是弦长 (2.35 米)。

where

P_{net} , M_{torque} are net pressure (normal to top surface of PV modules) and moment about torque tube;

ρ is the air density;

U is the 3-second gust wind speed at 10 m in open terrain;

K_{z_ASCE} is the exposure factor of 0.85 at tracker height (H) in open terrain as per ASCE 7;

A is the area of a Strip, Post, Quarter of a Row, Half of a Row, or Full Row (see Figure 2);

L is the chord length (2.35 m).

3.2 建议的风荷载系数 Recommended Wind Load Coefficients

3.2.1 静态风荷载系数 Static Wind Load Coefficients

对于主要结构构件和组件的设计, 建议采用表 1 中 GCR 为 40% 的风荷载系数。此表中提供的数据对应于图 2 中定义的行和平均面积。提供的值适用于 0° , 5° , 15° , 20° , 30° , 45° , 60° 倾角和 15° 倾角特殊工况。除 15° 倾角特殊工况外允许在所提供的倾角和平均面积之间进行线性插值。表 1 中的系数代表每个测试风向的每个平均面积的最不利值。负 C_P , 或“上吸力”, 被定义为垂直于 PV 上表面向外作用, 而正 C_P , 或“下压力”, 向内作用。该定义与 ASCE 7 规范一致。对扭矩或力矩 (C_M) 的情况, 提供了最不利绝对值。

For design of primary structural members and components, it is recommended that consideration be given to the wind load coefficients presented in Table 1 for GCR 40%. The data provided in this table corresponds to rows and averaging areas defined in Figure 2. Values are provided for the requested tilt angles of 0° , 5° , 15° , 20° , 30° , 45° , 60° , and 15° tilt special configuration. Linear interpolation between provided tilt angles and averaging areas is permitted except for the 15° tilt special configuration. The coefficients in Table 1 represent the worst-case values for each averaging area from the tested wind directions. Negative C_P , or “uplift”, is defined to act outward normal

to the upper PV surface, and positive C_p , or “downforce”, acts inward. This definition is consistent with the ASCE 7. In the case of torque or moment (C_M), the worst-case absolute value has been provided.

这些系数不包括任何动力（或惯性）效应。静荷载系数应加入适当的如章节 3.2.3 中所讨论的动态值。

These coefficients do not include any allowance for dynamic (or inertial) effects. The static coefficients should be increased by the appropriate dynamic values as discussed in Section 3.2.3.

3.2.2 动态风荷载系数 Dynamic Wind Load Coefficients

本报告表中的静态风荷载系数不包括 2.2.1 节中讨论的机制 #1 引起的共振（或惯性）荷载。动力（或惯性）风荷载系数由风抖振引起的增大的脉动风荷载确定，用于增加静态风荷载系数。图 3 至 10 提供了这些系数（GCR 40%）。

The tabulated static wind loading coefficients in this report do not include an allowance for resonant (or inertial) loading caused by Mechanism #1 discussed in Section 2.2.1. Dynamic (or inertial) wind load coefficients to increase the provided static coefficients have been determined based on the amplification of the fluctuating wind loads due to wind buffeting. These coefficients are provided in Figures 3 to 10 (GCR 40%).

对 0° 和 5° ， 15° ， 20° 和 30° ， 45° ， 60° 和 15° 倾角特殊工况的分组给出了动态系数作为折算频率（ fL/U ）的函数（多个阻尼比下），其中 f 是所研究的系统组件的模式（扭矩或弯曲）的固有频率（Hz）， L 是弦长（m）， U 是开阔地域 10 米高度处的 3 秒阵风风速（m/s）。如第 3.2.3 节所示，为每一行提供值，并将其应用于表 1 中的系数。

The dynamic coefficients are given for tilt angles of 0° , 5° , 15° , 20° , 30° , 45° , 60° and 15° tilt special configuration as a function of reduced frequency (fL/U) for multiple levels of damping, where f is the natural frequency (Hz) of the mode of interest (torque or bending), L is the chord length (m), and U is the 3-second gust wind speed (m/s) at 10 m height in open terrain. Values are given for each row and apply to the coefficients in Table 1 as shown in Section 3.2.3.

请注意，在确定折算频率（ fL/U ）时，风速（ U ）应在几个级别进行评估，包括但不限于：（a）用于保护状态的操作级别，（b）允许的应力水平，名义上相当于 25 至 50 年回归期，通常长于太阳能电池组列的预期寿命，（c）极限荷载级别。

Note that when determining the reduced frequency (fL/U), the wind speed (U) should be evaluated at several levels, including but not limited to (a) an operational level for stowing purposes, (b) allowable stress level, nominally equivalent to a return period of 25 to 50 years, which is typically longer than the expected life span of a solar array, and (c) the ultimate level.

对于北部地区的太阳能板阵列安装，如果设计需要考虑雪负荷，本报告所提供的动态风荷载系数仅适用于“无雪工况”。

For array installations in northern regions where snow loading is a design consideration, the provided dynamic wind load coefficients apply to the ‘zero snow case’ only.

3.2.3 风荷载的确定 Determination of Full-Scale Wind Loads

从本报告提供的系数获得太阳能板阵列的风荷载，应使用以下公式。注意，每个结构构件（例如，支撑柱）上的风荷载应该与其支撑的子区域成比例。

To obtain full-scale wind loads from the provided coefficients, the following equations should be used. Note that the wind loading on each structure member (e.g., posts) should be proportional to the tributary area it supports.

ASCE 7 安装 ASCE 7 Installation

$$F_N = q_z \cdot (C_{P_{Static}} \pm C_{P_{Dynamic}}) \cdot A$$

$$M_{torque} = q_z \cdot (C_{M_{Static}} \pm C_{M_{Dynamic}}) \cdot A \cdot L$$

此处，

F_N , M_{torque} 是法向力和扭矩管的力矩；

q_z 是根据 ASCE 7 规范对所选地貌在区域质心 A 高度 z 处的速度压力（即常数低于 15 ft, $K_d = 0.85$ ）；

A 和 L 在 3.1 节中定义；

“静态”系数见表 1；

“动态”系数在图 3 至 10 中给出，并用于导出最不利情况下的荷载。

where

F_N , M_{torque} are normal force and moment about the torque tube;

q_z is velocity pressure evaluated at height z at the centroid of the area, A, for selected exposure as per ASCE 7 procedure (i.e., constant below 15 ft and $K_d = 0.85$);

A and L are defined in Section 3.1;

“Static” coefficients are found in Table 1;

“Dynamic” coefficients are given in Figures 3 to 10 and apply with the sign that yields the worst-case loading.

3.2.4 开放区域和大型障碍物的影响 Effect of Open Areas and Large Obstructions

在这次研究中获得的风荷载适用于连续阵列。但是，可能存在作为通道和/或清除用的开放区域。如果这些开放区域的距离超过下表中给出的值，则阵列与它们相遇的地方形成新的周边区域。换句话说，如果行间隔足够的距离，则它们可以被视为单独的阵列，并且风荷载应适当地应用于每个阵列。但是，如果间隙足够小，则可以将阵列视为连续阵列，并且周边区域保持不变。如果大型障碍物（例如，逆变器室）高度不低于阵列高度并且最小水平尺寸不小于阵列高度，则将其视为阵列的一部分。

The wind loads obtained in this investigation are appropriate for a contiguous array. However, there could be open areas for access and/or clearance purposes. Where these open areas exceed a distance equal to the values given in the table below, new perimeter zones are formed where the array meets them. In other words, if the rows are separated by sufficient distances, they can be treated as separate arrays and the wind loads presented should be appropriately applied to each array. If, however, the gaps are sufficiently small, the array can be treated as a

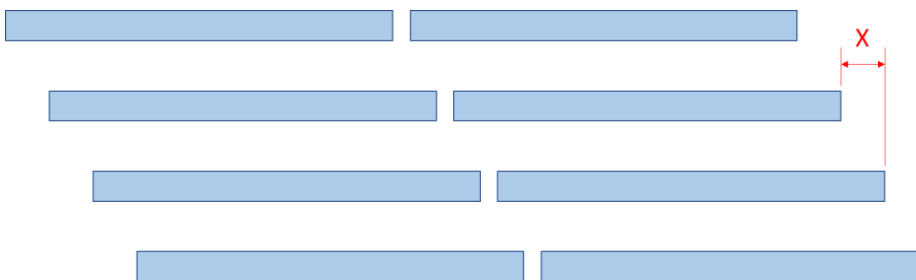
contiguous array, and the perimeter zones remain the same. Large obstructions (e.g., inverter houses) may be treated as part of the array if they are at least as high as the array and have a minimum horizontal dimension at least equal to the height of the array.

平均面积 Averaging Area	东-西向 East-West Direction	北-南向 North-South Direction
条和支撑柱 1 Strips and Post 1	$(2/GCR)*L$	$0.5*L$
四分之一行 Quarter Rows	$(2/GCR)*L$	n/a
半行 Half Rows	$(2/GCR)*L$	n/a
整行 Full Rows	$(2/GCR)*L$	n/a

3.2.5 步进阵列边缘 Stepped Array Edges

在该研究中获得的风荷载假设阵列具有矩形周边（即，没有台阶）。但是，沿阵列的北边和/或南边阵列可能需要安装成如下图中的“X”所示。在没有具体研究的情况下，“X”的最大允许值为 $2 * L$ ，在此范围内所提供的系数有效。

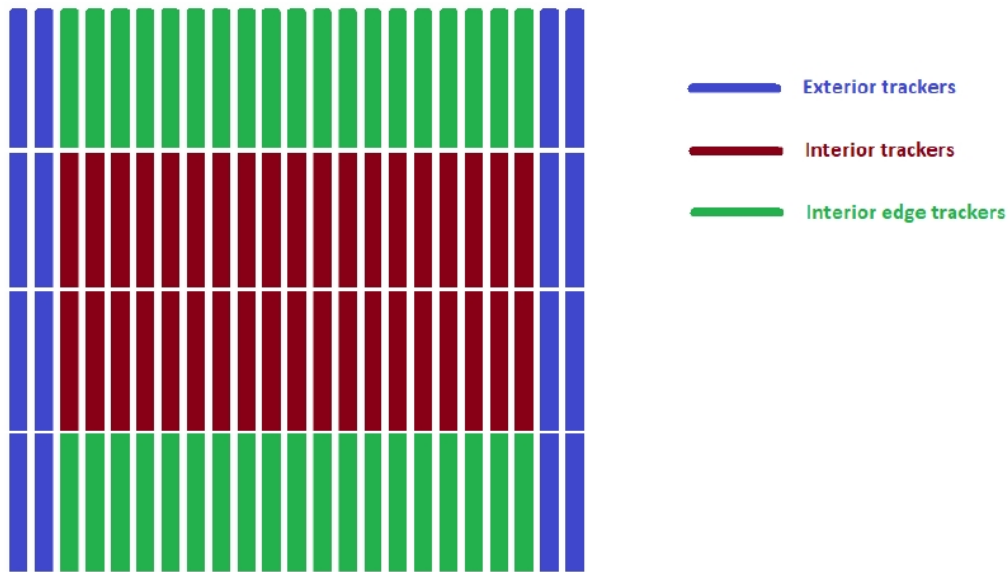
The wind loads obtained in this investigation assume that an array installation has a rectangular-shaped perimeter (i.e., no steps). However, there may be installations that required steps along the north and/or south edges of the array, as depicted by “X” in the diagram below. Without specific research, the maximum allowable size of “X” is $2*L$ for the provided coefficients to be valid.



3.2.6 大型阵列分区的扩展 Extension of Large Array Zoning

RWDI 的理解是，格瑞士使用下图所示的三个区域设计跟踪器阵列：“外部阵列”，“内部边沿阵列”和“内部列”。

It is RWDI's understanding that Grace Solar designs tracker arrays using the three zones shown in the image below: “Exterior Rows”, “Interior Edge Rows”, and “Interior Rows”.



本报告给出的第 1, 2, 7 和 8 行的最不利工况风荷载应用于设计外部阵列; 第 3 行至第 6 行的最不利工况风荷载应用于设计内部边沿阵列。RWDI 利用其空气动力学知识库来评估作用于内部阵列的风荷载。这些研究结果在下表中以乘法系数的形式表示, 并应用于从内部边沿阵列获得的静态风荷载系数。内部边沿阵列的动态系数同样适用于内部阵列。

The worst-case wind loads presented herein for Rows 1, 2, 7, and 8 should be used to design the Exterior Rows; the worst-case wind loads for Rows 3 to 6 should be used to design the Interior Edge Rows. RWDI has leveraged its aerodynamic knowledge base to assess the wind loads acting on the Interior Rows. The findings are presented as multiplication factors in the following table and are to be applied to the static wind load coefficients obtained for Interior Edge Rows. The dynamic coefficients for Interior Edge Rows equally apply to Interior Rows.

倾角 Tilt Angle	应用于内部边沿阵列来获取内部阵列风荷载的系数 Factor to Apply to Interior Edge Row Static Coefficients to Obtain Interior Row Static Coefficients				
	条 Strip	柱 Post	四分之一行 Quarter Row	半行 Half Row	整行 Full Row
0° to 60°	0.80	0.85	0.90	0.95	1.0

3.2.7 抗风设计过程 Process for Wind Design

为了帮助设计团队应用本报告中的建议, 附录 A 中给出了显示抗风设计过程的流程图。遵循此过程并未消除给定装置发生空气动力学不稳定的可能性(如第 2.2.2 和 2.2.3 节所述), 也不能充分预测气动弹性效应产生的自激力。为了降低系统遇到这些类型的不稳定性和/或气动弹性效应的风险, 基于系统刚度和/或阻尼比, 峰值总旋转应限制到小于 $\pm 5^\circ$ 。但是, 满足此阈值并不能消除由于过度运动而导致破坏的风险。



To assist the design team in applying the recommendations in this report, a flow chart showing the process for wind design is presented in Appendix A. Following this process does not eliminate the potential of aerodynamic instability (as discussed in Sections 2.2.2 & 2.2.3) occurring for a given installation, nor adequately predicts the self-excited forces from aeroelastic effects. To reduce the risk of the system experiencing these types of instability and/or aeroelastic effects, the peak total rotation should be constrained to less than $\pm 5^\circ$ based on system stiffness and/or damping. Meeting this threshold, however, does not eliminate the risk of failure due to excessive motions.

3.3 结果的适用性 **Applicability of Results**

3.3.1 风荷载建议的适用性 **Applicability of Wind Load Recommendations**

本报告中的风荷载建议不包括任何安全系数，适用于拟安装在标准且大致平坦的地貌系统。通常，平坦地貌是指两个方向上的坡度都小于 10%，或者用公式 26.8-1（来自 ASCE 7-16）能得出 $ASCE\ 7-16\ K_{zt} \leq 1.0$ 时。当坡度超过此阈值时，如在不进行其他测试或知识库评估情况下，应将所有行都视为周长行，并相对于地面坡度测量倾斜角。如果与标准地形条件相比显得突出的结构（如 ASCE 7 中包含的地貌类别图像所示）在阵列高度的 10 倍以内，则可能会发生一些荷载变化。如果是这种情况，应联系 RWDI 评估可能的影响，并确定可能的额外设计风压。此报告中的系数不应用于安装在凸起结构顶部的系统，例如建筑物的屋顶。

The wind loading recommendations in this report do not include any factor of safety and are applicable to the proposed system installed in generally flat terrain with standard conditions. Generally flat terrain is a slope less than 10% in both directions, or when $ASCE\ 7-16\ K_{zt} \leq 1.0$ using equation 26.8-1 (of ASCE 7-16). In lieu of additional testing or knowledgebase assessment, when the slope exceeds this threshold, all rows should be treated as perimeter rows with the tilt angle measured relative to ground slope. If structures that appear to be prominent compared to standard terrain conditions (as depicted in the exposure classification images contained in ASCE 7) are located within 10 times their height of the array, then some load changes could occur. If this is the case, RWDI should be contacted to comment on the probable effects and possibly to determine additional appropriate design wind pressures. The coefficients in this report should not be used for systems installed on top of a raised structure, such as the roof of a building.

所提供的系数适用的阵列和阵列凸起，其在东西方向上至少四行，并且最小尺寸不小于南北方向上的中心到中心行间距的四倍。对于其他阵列大小，当中心区域变化时，周边区域保持不变。第 3.2.4 节讨论了阵列中的开放区域和大型障碍物，第 3.2.5 节讨论了步进阵列边缘。

The provided coefficients apply to arrays and array protrusions with at least four rows in the east-west direction and a minimum dimension equal to four times the center-to-center row spacing in the north-south direction. For other array sizes, the perimeter zone remains the same, while the central zone changes. Open areas in the array and large obstructions are discussed in Section 3.2.4 and stepped edges are discussed in Section 3.2.5.

表 1 中列出的系数不包含共振（或惯性）荷载，应在总设计风荷载中考虑。动态（或惯性）风荷载系数如图 3 至 10 中所示，应与第 3.2.3 节中讨论的静态系数相结合。将惯性荷载考虑在内（并遵循附录 A 中的抗风设计过程）并未消除给定装置发生空气动力学不稳定性的可能（如第 2.2.2 和 2.2.3 节中所讨论的），也未充分预测来自气动弹性效应的自激力。为降低系统遇到这些类型的不稳定性和气动弹性效应的风险，扭转峰值应限制在小于 $\pm 5^\circ$ 。如果超过该阈值，则此处提供的风荷载将不再有效，并且可能需要使用气动弹性模型进行进一步研究。但是，满足此阈值并不能消除由于过度运动而导致破坏的风险。对于北部地区的阵列安装，设计需要考虑雪荷载，本报告所提供的动态风荷载系数仅适用于“无雪工况”。

The coefficients tabulated in Table 1 do not include an allowance for resonant (or inertial) loading, which should be accounted for in the total design wind loads. Dynamic (or inertial) wind load coefficients are presented in Figures 3 to 10, which should be combined with the static coefficients as discussed in Section 3.2.3. The inclusion of inertial loading does not eliminate the potential of aerodynamic instability (as discussed in Sections 2.2.2 & 2.2.3) occurring for a given installation, nor adequately predicts the self-excited forces from aeroelastic effects. **To reduce the risk of the system experiencing these types of instability and aeroelastic effects, the peak rotation should be constrained to less than $\pm 5^\circ$. If this threshold is exceeded then the wind loading presented herein will no longer be valid, and further research using an aeroelastic model may be necessary. Meeting this threshold, however, does not eliminate the risk of failure due to excessive motions.** For array installations in northern regions where snow loading is a design consideration, the provided dynamic wind load coefficients apply to the 'zero snow case' only.

ASCE 7 标准详尽地提供了确定适当设计荷载的步骤。ASCE 7 标准中提供的荷载组合系数适用于将不同的荷载组合在一起，例如雪，风和地震。在美国大多数地方，使用 ASCE 7 步骤中 $K_d = 0.85$ 的方向因子是合适的。

The ASCE 7 Standard provide comprehensive procedures for determining appropriate design loads. The load combination factors provided in the ASCE 7 Standard are appropriate for combining different loads together, such as snow, wind, and seismic. The use of the directionality factor of $K_d = 0.85$ in the ASCE 7 procedure is adequate for most locations in the United States.

ASCE 7 中的高度系数 K_z 考虑了给定结构的地貌和高度。该报告中的系数基于低于 15 英尺的恒定高度系数，与 ASCE 7 一致。因此，为了获得适当的太阳能板阵列的风荷载，应使用 ASCE 7 指定的 K_z 值。例如，对于标称高度为 15 英尺或更低的开阔地貌阵列， K_z 应等于 0.85。

The exposure factor K_z in ASCE 7 accounts for the exposure and height of a given structure. The coefficients in this report are based on a constant exposure factor below 15 ft, consistent with ASCE 7. Therefore, to obtain the appropriate full-scale wind loads, the K_z value specified by ASCE 7 should be used. For example, K_z should equal 0.85, for arrays in open exposure with a nominal height of 15 ft or less.

3.3.2 跟踪系统冗余范围 Tracker System Tolerances

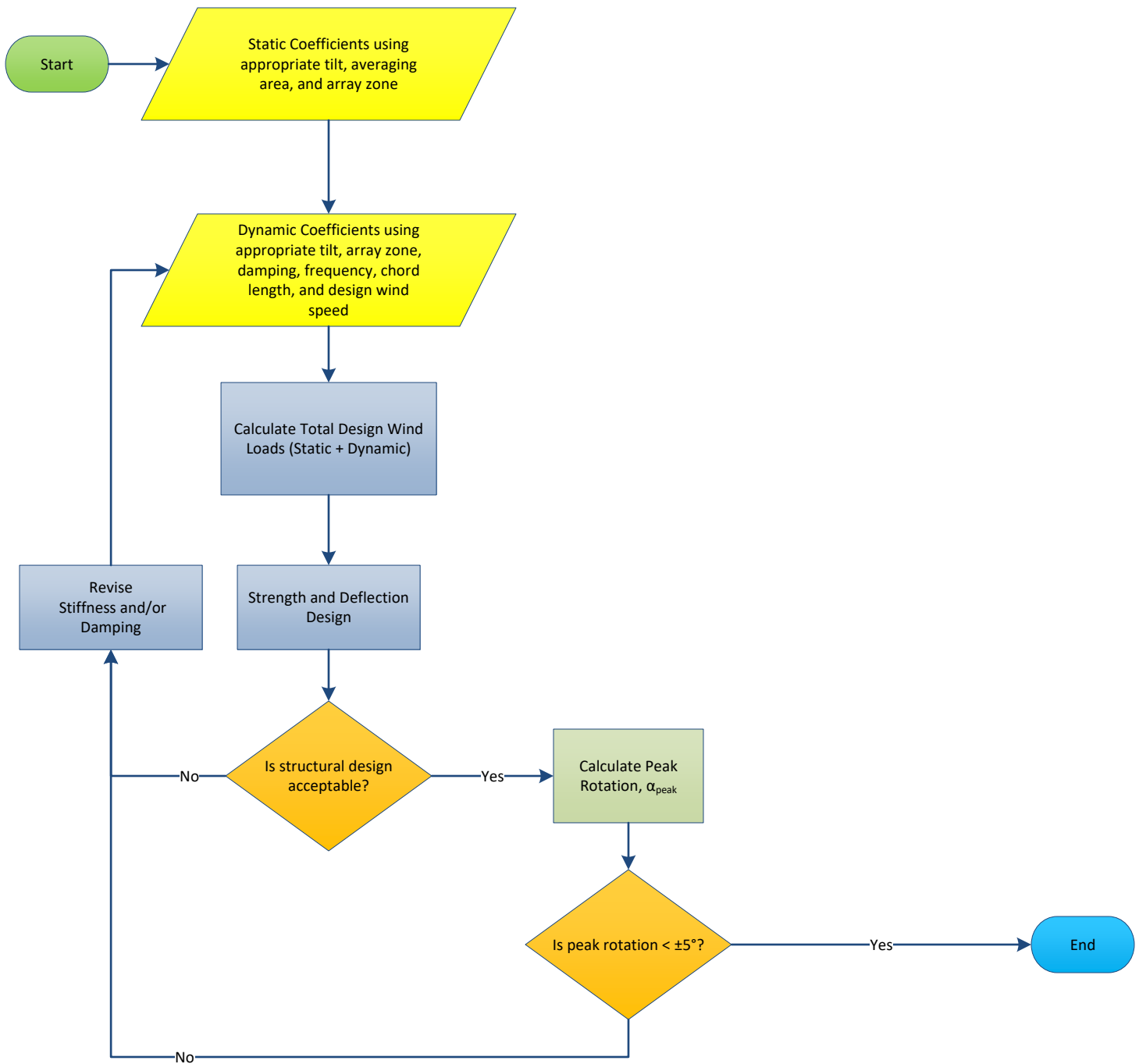
本报告中的风荷载系数适用于格瑞士太阳能地面安装的单轴跟踪系统，如 RWDI 于 2020 年 10 月 13 日收到的图纸所示，以及随后与设计团队的讨论。下表提供了关键尺寸的冗余度，在此范围内仍可使用此报告中的系数。如果超出所列冗余度，则可能需要进一步的风洞研究来准确定义本报告中的数据与其他参数的数据之间的关系。



The wind load coefficients in this report are applicable for the GRACE SOLAR Ground Mounted Single-Axis Tracker System, shown in the drawings received by RWDI on October 13, 2020, and subsequent discussions with the design team. The following table provides tolerances for the key dimensions such that the coefficients in this report can still be used. Further wind tunnel research may be required to accurately define the relationship between the data in this report and those for other parameters, if outside the listed tolerances.

参数 Parameter	值 Value	适用的冗余/范围 Applicability Tolerance / Range
阵列高度 Array Height (H)	1.76 m	±10%
弦长 Chord Length (L)	2.35 m	±10%
倾角 Tilt Angle (θ)	0°, 5°, 15°, 20°, 30°, 45°, 60°, and 15° special Configuration	除 15 度特殊倾角工况之外, 表 1 中给出的角度之间允许线性插值 Linear interpolation permitted between angles presented in Table 1, except for the 15° tilt special configuration
行长度 Row Length	95 m	±20%
地面覆盖率 Ground Cover Ratio (GCR)	40%	±10%
板开洞率 Table Openness Ratio (open/gross)	0 (solid)	≤0.10

Process for Wind Design



Note:

Following this process does not eliminate the potential of aerodynamic instability occurring for a given installation, nor adequately predicts the self-excited forces from aeroelastic effects.