# 基于 OPTShip-SJTU 的集装箱船船型优化设计

缪爱琴, 漆小舟, 陈泰文, 万德成

# (上海交通大学 船舶海洋与建筑工程学院 海洋工程国家重点实验室 高新船舶与深海开发装备协同创新中心)

**摘要**:船舶阻力性能是船舶重要的水动力性能之一。它与造船实际工程密切相关,可以通过船型优化设计出低阻力的优 良船型。本文基于课题组自主开发的船型优化软件 OPTShip-SJTU,以某集装箱船船模为母型船,对船舶首部和后半体同时 进行优化。通过自由变形(FFD)对船型变换,优化过程中对船舶排水体积变化进行约束(变化量范围±0.4%),寻求两个指 定航速下的总阻力线性组合最优的船型。船舶阻力评估采用课题组自主研发的基于 RANS 方法的粘性 CFD 求解器 naoe-FOAM-SJTU 进行求解,优化算法分别采用两种全局优化算法: PSO 和 GA 算法。最终得到优化船型。

#### 关键词: RANS; OPTShip-SJTU; 阻力性能; 船型优化

## 1引言

国际海事组织 IMO 引入能源效率设计索引 EEDI(Energy Efficiency Design Index)直接对船舶快速性 和操纵性等水动力性能提出了更高的要求。而船舶线型对水动力性能有重要的影响。因此在船舶设计的初 始阶段,基于船舶水动力性能的船型优化设计是必要的。当确定船舶线型后,船舶的许多设计工作才能继 续进行下去,如总布置设计、机舱布置、舱室内部舾装等。所以,船舶线型优化设计是船舶设计最基本、 最核心的一个环节,并且朝着绿色、节能、安全的方向加快创新发展,为中国船舶工业的转型升级提供技 术支持,实现船舶创新设计。

传统的船舶线型优化设计有以下几种方法:1) 通常是根据所要设计的船舶类似的、已经营运的、已知 其性能的一条或者多条优秀船舶(母型船)改变其主尺度、横剖面面积曲线等从而改变线型,得到符合设 计船要求的新船型。再根据母型船的资料,预估新船型的性能。2) 如若缺乏母型资料,船舶工程师可根据 新船的具体要求和线型生成的基本原则,自行绘制船舶线型。工程师在某种程度上参考性能尺度不完全一 样的现有船型同时根据自身的设计经验进行船舶线型设计。3) 根据美国的陶德系列 60、英国的 BSRA 系 列、荷兰的 NSMB、瑞典的 SSPA 和日本的 SR45 系列船型库以及我国公开发表的系列船型库:我国沿海 货轮船模系列试验、我国长江船系列试验等选择与新船特征相近的系列船型图谱进行设计。通过以上方法 得到初步的船型,然后制作船模进行船模试验验证其各项性能是否达标,如此往复。传统的设计模式强烈 依赖于母型库以及船舶工程师的设计经验,同时这样的船舶线型设计为了满足设计技术要求,需要反复修 改船型、反复校核船型性能,设计周期长、成本较高,对于如何改进船型也并未提供科学的优化依据

随着船舶与海洋工业的蓬勃发展,传统的船舶线型优化设计方法已无法满足船舶的创新设计理念。造船工程师迫切需要一套崭新的具有科学依据的船型优化设计方法。近些年,基于 CFD 的优化设计理念成为热潮<sup>[1]-[4]</sup>。然而为了通过船型优化设计得到水动力性能最佳的改良船型,设计者往往需要进行大量的水动力性能数值评估,这将导致设计过程所耗费的计算成本和时间大大增加。为了使得基于 CFD 的优化设计理念在船舶市场更具潜力和竞争力,必须采用一套快速、实用且有效的基于 CFD 的船舶水动力性能优化工具,以使得初步设计阶段船型确定的及时性和实用性。

为此,万德成教授课题组自主开发了船型优化设计软件 OPTShip-SJTU,是基于船舶水动力性能的专业优化工具。主要由四个模块组成:船型变换,水动力性能评估,近似模型建立,单目标(或多目标)优化求解。船型变换目前的主要方法有平移法、径向基函数、自由变形等;水动力性能主要是基于势流理论

1

(利用课题组已有的基于 Nuemann-Michell 的 NMShip-SJTU 求解器)和基于粘流的 CFD 计算方法(利用 课题组已有发展较为成熟的基于 RANS 开发的 naoe-FOAM-SJTU 求解器);近似模型主要是为了解决目标 函数评价的时间长以及评价的成本高而提出来的,主要有响应面方法,Kriging 模型等;优化方法主要有传 统的基于梯度的优化算法和基于随机搜索思想的启发式优化算法。常见的启发式优化算法包括模拟退火算 法,进化算法,遗传算法以及粒子群算法。传统的优化算法需要求解目标函数的梯度,对于有确定目标函 数形式的优化问题具有很强的适用性。该求解器已经成功应用于一些典型船模(Wigley, KCS, DTMB 5415, Delft 等船型)<sup>[5]-[7]</sup>水动力性能优化,包括阻力性能,耐波性能,伴流性能等方面。另外,课题组采用超级 计算机进行并行计算。大大降低优化时长。

本文将采用该优化求解器对某集装箱船两个航速下的总阻力线性之和(以 Fr=0.2343 (30%)和 Fr=0.1834 (70%)两个速度下阻力线性之和为目标函数)优化,对船舶首部和尾部同时进行优化。船型变换使用 FFD 方法进行。总阻力性能由基于 RANS 方法的粘性 CFD 求解器 naoe-FOAM-SJTU 进行评估。优化算法同时采用粒子群算法和遗传算法确保优化迭代收敛的可靠性。优化过程中将船舶排水体积变化控制在±0.4%。

## 2 优化流程与方法

通常,基于 OPTShip-SJTU 求解器的船型优化流程:首先选择合适的船型变换技术对母型船进行变换, 并以相关 k 个几何参数为设计变量,同时人为确定一个 k 维设计空间,在优化迭代前,为了降低计算成本, 引入试验设计和近似技术:通过科学地在设计空间布满有限个样本点(一般地,5k~10k 个样本点足矣), 然后通过势流方法或者粘流方法对系列对应新船型进行水动力性能评估,从而以已知样本点构建近似模型, 以便在后续优化进程中,目标函数无需通过高精度数值模拟而是调用近似模型进行计算,大大加快优化进 程。优化方法目前已有很多成熟的算法可供选择。最终获得优化船型。如果未得到符合要求的优化船型则 再根据优化进程反馈的信息重新修改优化方案,循环往复。求解器的基本结构图如图 1。接下来将从四个 模块一一介绍本文所采用的具体方法。



图 1 OPTShip-SJTU 求解器的基本结构图

#### 2.1 船型变换方法: FFD 方法

本文采用自由变形方法(Free-form deformation, FFD)对母型船进行船型变换。FFD 方法是由 Sederberg 和 Parry 在 1986 年提出的一种网格自由变形方法。已经被广泛应用于包括船舶几何重构在内的各个领域。 其基本思想是: 1) 首先选定一个格子(Lattice),格子的大小与位置确定了待变形区域的大小与位置;

2) 在格子内选定一系列控制点,并通过 Bernstein 多项式建立船体表面点坐标与控制点坐标间的关系; 3) 以部分控制点位移量位设计优化变量,通过移动控制点位置,来实现船体曲面变形。

FFD 方法涉及的设计变量较少,曲面变化非常灵活,并且对变形区域的大小和位置严格可控,同时该 方法简洁明快,易于编程实现。详细推导可参见[5]

### 2.2 水动力性能评估方法

本文采用基于雷诺平均N-S方程(RANS)的naoe-FOAM-SJTU 求解器进行船舶的静水阻力求解<sup>[8]-[9]。</sup>  $\nabla \cdot \mathbf{U} = \mathbf{0}$ 

(1)

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla \cdot (\rho(\mathbf{U} - \mathbf{U}_g)\mathbf{U} = -\nabla p_d - g \cdot x \nabla \rho + \nabla \cdot (\mu_{eff} \nabla \mathbf{U}) + (\nabla \mathbf{U}) \cdot \nabla \mu_{eff} + f_\sigma$$
(2)

式中:U表示速度场;Ug表示网格节点的速度;pd=p-pg·x表示动压力场,由总压力减去静水压力得 到。 $\rho$ 表示空气和水两项流体的混合密度;g表示重力加速度; $\mu eff = \rho(\nu + \nu t)$ 表示有效动力粘性系数,其中 ν表示运动粘性系数, νt 表示涡粘系数; fo 是两相流模型中的表面张力项。控制方程采用 PISO 算法处理速 度与压力的耦合。采用 Rhie 和 Chow 提出的同位网格法代替传统的交错网格法从而节省了网格信息的存储 量。

优化前首先采用 naoe-FOAM-SJTU 求解器对母型船在两个航速下的阻力性能进行了预报,并进行了网 格收敛性验证( $R_{G}<1$ )(见表 1),最终采用中等网格进行计算。计算流域范围-L<x<4L,0<y<L,-L<z<0.5L。 如图 2。(注:此处结果均为基于船模的数值计算所得,见章节 3)

		表 1 网格收敛性验证		
	网枚旱(下)		Fr=0.2343	
	网俗里(刀)	Rp	Rv	Rt
细网格	552.58	2.9814	14.1843	17.1657
中网格	198.05	3.3308	13.7682	17.0990
粗网格	68.76	3.4118	13.0275	16.4393
E21=Rt(中)-Rt(细	])			-0.066662356
E32=Rt(粗)-Rt(中	1)			-0.659737645
$R_G = E21/E32$				0.10

网板市体性心汗





图 2 CFD 数值模拟采用的中等网格划分

### 2.3 Kriging 近似技术

为了降低计算成本,减少优化进程中目标函数响应时长,采用近似模型进行预报迭代过程中个体(或 粒子)目标函数值,本文中采用 Kriging 方法构建近似模型。从统计意义上说,Kriging 方法是从设计变量 相关性和变异性出发,在设计空间内对设计变量的取值进行无偏、最优估计的一种方法;从插值角度讲是 对空间分布的数据求线性最优、无偏内插估计的一种方法。Kriging 模型具有较好的适应性,可以广泛用于 对低阶和高阶非线性问题的拟合。

构建近似模型之前,首先需要在设计空间内合理的选择足够的样本点。试验设计就是一种方法,试验 设计是数理统计学的应用方法之一,它的主要内容是讨论如何合理地安排试验、取得数据,然后进行综合 的科学分析,构建近似模型,从而达到尽快获得最优方案的目的。本文采用最优化拉丁方方法进行试验设 计,拉丁方试验设计将因素按水平竖排成一个随机矩阵,即拉丁方矩阵,在同一列中任何因素的水平均无 重复。针对随机抽样的不稳定性,出现了:中心化 LHS、对称 LHS、列正交 LHS 以及最优 LHS 等改进, 它们都是就其中某一测度进行的改进。最优化拉丁方试验设计方法采用正交性较好的初始解,优化时综合 考虑拉丁方矩阵的正交性和均匀性,包括初始解构造和拉丁方矩阵的优化两个步骤<sup>[5]</sup>。

### 2.4 全局优化算法

由于局部优化策略容易陷入局部最优解,而当前包括船舶工程在内的诸多工程科学发展迅速,船体线 型设计也已经很难在局部寻找到更优设计。因此,有效的全局优化算法亟需被应用到船体线型优化设计中。 遗传算法作为一种较为成熟的全局优化算法,在很多工程优化问题上已有成功应用。

粒子群优化算法(Particle Swarm Optimization, PSO)同遗传算法类似,也是一种基于群体叠代的,但 并没有遗传算法用的交叉以及变异,而是粒子在解空间追随最优的粒子进行搜索。PSO 的优势在于简单, 容易实现,无需梯度信息,参数少,特别是其天然的实数编码特点特别适合于处理实优化问题。同时又有 深刻的智能背景,既适合科学研究,又特别适合工程应用。

本文为了确保优化结果可靠,同时采用上述两种全局优化算法分别进行优化,两种算法的优化参数配置如表 2,3 所示。

表 2 遗传算法基本参数配置							
每代个体数	遗传率	交叉率	变异率	最大迭代数			
50	0.2	0.8	0.2	200			
	表3 粒	子群优化算法基本	参数配置				
每代粒子数	个体	认知	社会认知	最大迭代数			
20	0	.5	1.25	200			

## 3船型优化实例

本文拟对某集装箱船进行船型优化,采用模型尺度进行优化设计。实船与船模主尺度如表 4.

主尺度	符号与单位	实船	船模
缩尺比	λ	42	2
垂线间长	L <sub>pp</sub> (m)	260	6.1905
船宽	B (m)	32.22	0.7671
吃水	T (m)	12	0.2857
湿面积	S (m <sup>2</sup> )	5680.43	3.22
排水量	$\nabla$ (m <sup>3</sup> )	64378.26	0.8690
傅氏数	Fr	0.1834 和	0.2343

表 4 实船与船模主尺度

技术要求:

1、以 Fr=0.2343 (30%) 和 Fr=0.1834 (70%) 两个速度为优化点,括号内为权重,目前阶段仅考虑阻力 优化;

2、L<sub>pp</sub>/B/T 保持不变,实船排水体积变化控制在±300m<sup>3</sup>即排水体积变化控制在±0.4%;无其他限制条件。

所以本文优化设计的目标函数明确为:

$$f_{obi} = 0.7R_T (Fr = 0.1834) + 0.3R_T (Fr = 0.2343)$$
(3)

约束条件为:

$$\delta \nabla = \pm 0.4\% \tag{4}$$

本文同时对首尾部进行优化,对首部进行船型变化时同样采用两个大小不一的格子,一个格子中的部 分控制点沿着船长和吃水方向移动,另一个格子中的部分控制点沿着船宽方向移动。尾部船型变换也采用 两个大小不一的格子,部分控制点沿着船长和船宽方向移动,进而使得船体表面形状发生变化,尾部采用 两个格子的主要原因是控制型宽不变以及尾部桨轴位置不变。如图3所示。其中红色的点为可移动控制点, 绿色的点为固定点(确保边界曲面光顺)。因此,后面优化设计采用五个设计变量(均为控制点的不同方向 位移量)。注:此处的量级都是相对船长进行了无因次化。如表5。





(c)



船长方向变换



吃水方向变换



船宽方向变换



船长方向变换

船宽方向变换

图 3	FFD 方法的可变区域和控制点分布

衣 3	衣 5								
设计变量	变化方向	下界	上界						
	x1	-0.01	0.01						
首部	z1	-0.007	0.008						
	y1	-0.01	0.01						
民刘	x2	-0.01	0.01						
定即	y2	-0.01	0.01						

長5 基于 FFD 变形参数的设计变量及范围

本算例中共计五个设计变量,通过最优化拉丁方方法(OLHS)选取 35个样本点充满整个空间,如图 4。将对应的这 35个新船型进行数值计算获得两个速度下阻力值,从而得到目标函数(见表 6),构建两个 近似模型(目标函数以及约束条件)。从而在优化进程中直接采用简单的代数公式计算目标函数和约束条件,加快优化进程。



图 4 基于 OLHS 产生的 35 个样本点分布 表 6 基于 RANS 方法的 35 个船型对应的总阻力情况

	18kn		23kn		约束 约束 目标函数 约束 条件		变化量			
压阻力	摩擦阻力	总阻力	压阻力	摩擦阻力	总阻力	<b>DD</b> *0.7   <b>D</b> *0.2/N	$\nabla /m^3$	<b>D</b> +0/	$\nabla 0$	_
/N	/N	$R_{tl}/N$	/N	/N	$R_{t2}/N$	$K_{1} = K_{1} = 0.7 + K_{12} = 0.5/N$	∨ / <b>m</b> ²	Kt%	∨ %o	

1   2.0068   8.9581   10.9648   3.7218   13.8741   17.5959   12.9542   0.4399   2.93%   1.20%     2   19.089   8.8888   10.7927   3.3910   13.7278   17.1188   12.6005   0.4324   0.83%   -0.54%     3   1.7461   8.8772   10.6234   3.2927   13.7457   17.1559   12.4510   0.4318   -0.75%   -0.66%     5   1.9360   8.8843   10.8203   3.4277   13.7445   17.1702   12.752   0.4407   1.11%   1.38%     6   1.8103   8.8510   10.6613   3.4576   13.8846   17.3201   12.8374   0.4374   2.00%   0.62%     8   1.7666   8.8772   10.6438   3.4756   17.057   12.6844   0.4368   0.37%   0.48%     10   1.9343   8.8511   10.7571   3.2808   13.7676   17.0484   12.6057   0.4311   0.63%   0.83%     11   1.8765   8.8776   10.7571											
19089   8.8838   10.7927   3.3910   13.7278   17.1188   12.6905   0.4324   0.8394   0.5495     3   1.7461   8.8772   10.6234   3.2922   13.7637   17.0559   12.5531   0.4316   0.2696   0.71%     4   1.7703   8.8803   10.6506   3.0571   13.7280   16.8451   12.2910   0.4318   -0.75%   -0.68%     5   1.9300   8.8843   10.6613   3.1370   13.7035   16.8405   12.5151   0.4338   -0.56%   -0.21%     7   1.9465   8.9698   10.9163   3.4655   13.8027   17.1057   12.6350   0.4388   0.97%   0.48%     9   1.8598   8.9284   10.7842   3.3125   13.7032   17.1057   12.634   0.4388   0.97%   0.48%     10   1.9345   8.8376   10.7841   3.4952   17.1057   12.6184   0.4313   0.639%   0.58%     13   1.8454   8.8379   10.6791   3.6473<	1	2.0068	8.9581	10.9648	3.7218	13.8741	17.5959	12.9542	0.4399	2.93%	1.20%
3   1.7461   8.8772   10.6234   3.2922   13.7637   17.0559   12.5531   0.4316   -0.26%   0.071%     4   1.7703   8.8803   10.6606   3.0571   13.7280   16.7851   12.4910   0.4318   -0.75%   0.68%     5   1.9360   8.8843   10.8003   3.4257   13.7445   17.102   12.2521   0.4338   -0.56%   -0.21%     7   1.9465   8.9698   10.0613   3.1370   13.7035   16.8405   12.8374   0.4378   0.037%   0.42%     8   1.7666   8.8772   10.6438   3.4786   13.8027   17.2813   12.6350   0.4368   0.77%   0.48%     10   1.9343   8.8371   10.7841   3.4952   13.7662   17.2614   12.6657   0.4311   0.63%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%   0.58%	2	1.9089	8.8838	10.7927	3.3910	13.7278	17.1188	12.6905	0.4324	0.83%	-0.54%
4   1.7703   8.8803   10.6506   3.0571   13.7280   16.7851   12.4910   0.4318   -0.75%   -0.68%     5   1.9360   8.8843   10.8203   3.4257   13.7445   17.1702   12.7252   0.4407   1.11%   1.38%     6   1.8103   8.8510   10.6613   3.1370   13.7035   16.8405   12.28374   0.4338   -0.56%   -0.21%     7   1.9465   8.9698   10.0438   3.4765   13.7021   17.2813   12.6550   0.4388   0.37%   0.48%     9   1.8598   8.9284   10.7841   3.2808   13.7672   17.0444   12.6657   0.4311   0.63%   0.35%     10   1.9343   8.8531   10.7541   3.4922   13.7672   17.0144   12.6657   0.4311   0.5%   0.35%     12   1.7090   8.8136   10.5227   3.1537   13.6739   16.2716   12.4122   0.4338   0.25%   0.35%     14   1.8311   8.8479	3	1.7461	8.8772	10.6234	3.2922	13.7637	17.0559	12.5531	0.4316	-0.26%	-0.71%
5 1.9360 8.8843 10.8203 3.4257 13.7445 17.1702 12.7252 0.4407 1.11% 1.38%   6 1.8103 8.8510 10.6613 3.1370 13.7035 16.8405 12.5151 0.4338 -0.65% -0.21%   7 1.9465 8.8972 10.6438 3.4756 13.8027 17.1057 12.6834 0.4368 0.07% 0.48%   10 1.9343 8.8531 10.7874 3.2808 13.766 17.0184 12.6657 0.4311 0.63% 0.48%   11 1.8765 8.8776 10.7541 3.4922 13.7662 17.2614 12.7062 0.4337 0.96% 0.23%   12 1.7090 8.8136 10.5227 3.1537 13.673 16.6216 0.4388 0.25% 0.95%   13 1.8454 8.8592 10.0746 3.3415 13.772 17.0787 12.6168 0.4388 0.25% 0.95%   14 1.8114 8.859 10.6701 3.666 13.7273 16.9191 12.5129 0.4304 0.022% 0.30%	4	1.7703	8.8803	10.6506	3.0571	13.7280	16.7851	12.4910	0.4318	-0.75%	-0.68%
6   1.8103   8.8510   10.6613   3.1370   13.7035   16.8405   12.5151   0.4388   -0.56%   0.21%     7   1.9465   8.9698   10.9163   3.4655   13.8546   17.3201   12.8374   0.4374   2.00%   0.62%     8   1.7666   8.8772   10.6438   3.4786   13.8027   17.2813   12.6550   0.4368   0.39%   0.48%     9   1.8598   8.9284   10.7842   3.3125   17.7057   12.6834   0.4368   0.77%   0.48%     10   1.9343   8.851   10.7541   3.7622   17.2614   12.7062   0.4337   0.96%   0.23%     12   1.7090   8.816   10.5227   3.1575   16.7919   12.6168   0.4388   0.25%   0.95%     14   1.8311   8.8479   10.6791   3.0646   13.7273   16.7919   12.5129   0.4308   0.25%   0.95%     15   1.8747   8.853   10.7609   3.4222   13.754	5	1.9360	8.8843	10.8203	3.4257	13.7445	17.1702	12.7252	0.4407	1.11%	1.38%
7 1.9465 8.9698 10.9163 3.4655 13.8546 17.3201 12.8374 0.4374 2.00% 0.62%   8 1.7666 8.8772 10.6438 3.4786 13.8027 17.2813 12.6550 0.4368 0.39% 0.448%   9 1.8598 8.9224 10.782 3.3125 13.7932 17.1057 12.6854 0.4368 0.77% 0.48%   10 1.9343 8.8531 10.7741 3.4952 13.7676 17.2614 12.7062 0.4337 0.96% -0.23%   11 1.8765 8.88776 10.5227 3.1537 13.6739 16.8276 12.4142 0.4384 -0.58% 0.95%   13 1.8454 8.8592 10.7060 3.415 13.7371 16.719 12.6168 0.4388 0.25% 0.95%   15 1.8747 8.8853 10.7000 3.422 13.7541 16.917 12.6683 0.4384 0.02% 0.07%   16 1.8603 8.8668 10.7271 3.1803 13.7514 16.9317 12.5187 0.4336 0.22% <th>6</th> <td>1.8103</td> <td>8.8510</td> <td>10.6613</td> <td>3.1370</td> <td>13.7035</td> <td>16.8405</td> <td>12.5151</td> <td>0.4338</td> <td>-0.56%</td> <td>-0.21%</td>	6	1.8103	8.8510	10.6613	3.1370	13.7035	16.8405	12.5151	0.4338	-0.56%	-0.21%
8   1.7666   8.8772   10.6438   3.4786   13.8027   17.2813   12.6350   0.4368   0.39%   0.48%     9   1.8598   8.9224   10.7882   3.3125   13.7932   17.1057   12.6634   0.4368   0.77%   0.48%     10   1.9343   8.8531   10.7874   3.2008   13.7676   17.0414   12.6657   0.4311   0.63%   -0.33%     11   1.8705   8.8776   10.7541   3.4952   13.7676   17.2614   12.7062   0.4337   0.96%   -0.23%     12   1.7090   8.8136   10.5227   3.1537   13.6739   16.8276   12.4142   0.4328   0.25%   0.95%     14   1.8311   8.8479   10.6791   3.0464   13.7273   16.7919   12.5129   0.4388   0.25%   0.95%     15   1.8747   8.8853   10.7070   3.1803   13.7514   16.9317   12.5885   0.4331   0.02%   0.30%     17   1.9075   8.8511	7	1.9465	8.9698	10.9163	3.4655	13.8546	17.3201	12.8374	0.4374	2.00%	0.62%
9   1.8598   8.9284   10.7882   3.3125   13.7932   17.1057   12.6834   0.4368   0.77%   0.48%     10   1.9343   8.8531   10.7874   3.2808   13.7676   17.0484   12.6657   0.4311   0.63%   -0.83%     11   1.8765   8.8776   10.7541   3.4952   13.7672   17.2614   12.7062   0.4337   0.96%   -0.23%     12   1.7090   8.8136   10.5227   3.1537   13.6739   16.8276   12.4142   0.4324   -1.36%   -0.53%     13   1.8454   8.8592   10.7046   3.3415   13.7273   16.7919   12.5129   0.4308   0.25%   -0.39%     15   1.8474   8.8531   10.7671   3.1603   13.7514   16.9317   12.5885   0.4381   0.02%   -0.39%     16   1.8603   8.8668   10.7271   3.1803   13.6913   12.6137   0.4360   0.22%   0.30%     17   1.9075   8.8511   10.5722<	8	1.7666	8.8772	10.6438	3.4786	13.8027	17.2813	12.6350	0.4368	0.39%	0.48%
10   1.9343   8.8531   10.7874   3.2808   13.7676   17.0484   12.6657   0.4311   0.63%   -0.83%     11   1.8765   8.8776   10.7541   3.4952   13.7662   17.2614   12.7062   0.4337   0.96%   -0.23%     12   1.7090   8.8136   10.5227   3.1537   13.6739   16.8276   12.4142   0.4324   -1.36%   -0.54%     13   1.8454   8.892   10.7046   3.3415   13.7372   17.0787   12.6168   0.4388   0.25%   0.95%     14   1.8311   8.8479   10.6791   3.0646   13.7273   16.7919   12.5129   0.4308   -0.5%   -0.37%     15   1.8747   8.8853   10.7600   3.4222   13.7574   16.917   12.5885   0.4334   0.02%   -0.37%     16   1.8603   8.8668   10.7271   3.1803   13.7327   16.9425   12.6137   0.4321   -0.8%   -0.67%     19075   8.8511   10.5	9	1.8598	8.9284	10.7882	3.3125	13.7932	17.1057	12.6834	0.4368	0.77%	0.48%
11 1.8765 8.8776 10.7541 3.4952 13.7662 17.2614 12.7062 0.4337 0.96% -0.23%   12 1.7090 8.8136 10.5227 3.1537 13.6739 16.8276 12.4142 0.4324 -1.36% -0.54%   13 1.8454 8.8592 10.7046 3.3415 13.7372 17.0787 12.6168 0.4388 0.25% 0.95%   14 1.8311 8.8479 10.6791 3.0646 13.7273 16.7919 12.5129 0.4308 -0.5% -0.8%   15 1.8747 8.8853 10.7600 3.4222 13.7554 17.1776 12.6885 0.4334 0.02% -0.30%   16 1.8603 8.8668 10.7271 3.1803 13.727 16.9425 12.6137 0.4360 0.22% 0.30%   18 1.8126 8.7831 10.619 3.3660 13.6313 16.9913 12.5187 0.4327 -0.53% -0.46%   19 1.7891 8.7875 10.612 3.1433 13.6805 16.8238 12.4757 0.4327 0	10	1.9343	8.8531	10.7874	3.2808	13.7676	17.0484	12.6657	0.4311	0.63%	-0.83%
12 1.7090 8.8136 10.5227 3.1537 13.6739 16.8276 12.4142 0.4324 -1.36% -0.54%   13 1.8454 8.8592 10.7046 3.3415 13.7372 17.0787 12.6168 0.4328 0.25% 0.95%   14 1.8311 8.8479 10.6791 3.0646 13.7273 16.7919 12.5129 0.4308 -0.58% -0.89%   15 1.8747 8.8533 10.7600 3.4222 13.7554 17.1776 12.6853 0.4341 0.02% -0.30%   16 1.8603 8.8668 10.7271 3.1803 13.7514 16.917 12.5885 0.4334 0.02% -0.30%   17 1.9075 8.8511 10.7585 3.2098 13.7327 16.6425 12.6137 0.4300 0.22% 0.30%   18 1.8126 8.7831 10.572 3.1027 13.6669 16.7696 12.4314 0.4305 -1.23% 0.97%   20 1.7947 8.8175 10.6122 3.1432 13.7066 17.1198 12.5294 0.4365 <td< td=""><th>11</th><td>1.8765</td><td>8.8776</td><td>10.7541</td><td>3.4952</td><td>13.7662</td><td>17.2614</td><td>12.7062</td><td>0.4337</td><td>0.96%</td><td>-0.23%</td></td<>	11	1.8765	8.8776	10.7541	3.4952	13.7662	17.2614	12.7062	0.4337	0.96%	-0.23%
13   1.8454   8.8592   10.7046   3.3415   13.7372   17.0787   12.6168   0.4388   0.25%   0.95%     14   1.8311   8.8479   10.6791   3.0646   13.7273   16.7919   12.5129   0.4308   -0.58%   -0.89%     15   1.8747   8.8853   10.7600   3.4222   13.7554   17.1776   12.6853   0.4381   0.79%   0.77%     16   1.8603   8.8668   10.7271   3.1803   13.7327   16.9425   12.6137   0.4360   0.22%   0.30%     17   1.9075   8.8511   10.5722   3.1027   13.669   16.7696   12.4314   0.4305   -1.23%   -0.97%     20   1.7947   8.8175   10.6122   3.1432   13.7066   17.1198   12.5294   0.4365   -0.45%   0.40%     21   1.7341   8.8220   10.5621   3.4132   13.6937   12.5776   0.4307   -0.07%   0.91%     23   1.856   8.8202   10.7824 </td <th>12</th> <td>1.7090</td> <td>8.8136</td> <td>10.5227</td> <td>3.1537</td> <td>13.6739</td> <td>16.8276</td> <td>12.4142</td> <td>0.4324</td> <td>-1.36%</td> <td>-0.54%</td>	12	1.7090	8.8136	10.5227	3.1537	13.6739	16.8276	12.4142	0.4324	-1.36%	-0.54%
14 1.8311 8.8479 10.6791 3.0646 13.7273 16.7919 12.5129 0.4308 -0.58% -0.89%   15 1.8747 8.8853 10.7600 3.4222 13.7554 17.1776 12.6853 0.4381 0.79% 0.77%   16 1.8603 8.8668 10.7271 3.1803 13.7514 16.9317 12.5185 0.4334 0.02% -0.30%   17 1.9075 8.8511 10.6755 3.2098 13.7327 16.9425 12.6137 0.4360 0.22% 0.30%   18 1.8126 8.7893 10.6019 3.3600 13.6313 16.9913 12.5187 0.4327 -0.53% -0.46%   19 1.7891 8.7831 10.5722 3.1027 13.6669 16.7696 12.4314 0.4305 -1.23% -0.97%   20 1.7947 8.8175 10.6122 3.1432 13.7066 17.1198 12.5294 0.4365 -0.45% 0.40%   21 1.7341 8.820 10.5621 3.4132 13.6973 16.8901 12.5335 0.4307 <	13	1.8454	8.8592	10.7046	3.3415	13.7372	17.0787	12.6168	0.4388	0.25%	0.95%
15 1.8747 8.8853 10.7600 3.4222 13.7554 17.1776 12.6853 0.4381 0.79% 0.77%   16 1.8603 8.8668 10.7271 3.1803 13.7514 16.9317 12.5885 0.4334 0.02% -0.30%   17 1.9075 8.8511 10.7585 3.2098 13.7327 16.9425 12.6137 0.4360 0.22% 0.30%   18 1.8126 8.7893 10.6019 3.3600 13.6313 16.9913 12.5187 0.4327 -0.53% -0.46%   19 1.7891 8.7831 10.5722 3.1027 13.6669 16.7696 12.4314 0.4305 -1.23% -0.97%   20 1.7947 8.8175 10.6122 3.1433 13.6805 16.8238 12.4757 0.4321 -0.88% -0.60%   21 1.7341 8.820 10.5621 3.4132 13.7066 17.1198 12.5776 0.4307 -0.47% -0.18%   23 1.8156 8.8508 10.6663 3.1929 13.6973 16.8901 12.535 0.4339 <	14	1.8311	8.8479	10.6791	3.0646	13.7273	16.7919	12.5129	0.4308	-0.58%	-0.89%
16   1.8603   8.8668   10.7271   3.1803   13.7514   16.9317   12.5885   0.4334   0.02%   -0.30%     17   1.9075   8.8511   10.7585   3.2098   13.7327   16.9425   12.6137   0.4360   0.22%   0.30%     18   1.8126   8.7893   10.6019   3.3600   13.6313   16.9913   12.5187   0.4327   -0.53%   -0.46%     19   1.7891   8.7831   10.5722   3.1027   13.6669   16.7696   12.4314   0.4305   -1.23%   -0.97%     20   1.7947   8.8175   10.6122   3.1433   13.6605   16.8238   12.4757   0.4321   -0.88%   -0.60%     21   1.7341   8.820   10.5621   3.4132   13.7665   17.1198   12.5294   0.4365   -0.45%   0.40%     22   1.8859   8.8222   10.7082   3.2509   13.6973   16.8901   12.5335   0.4337   1.09%   0.73%     24   1.8805   8.937	15	1.8747	8.8853	10.7600	3.4222	13.7554	17.1776	12.6853	0.4381	0.79%	0.77%
17 1.9075 8.8511 10.7585 3.2098 13.7327 16.9425 12.6137 0.4360 0.22% 0.30%   18 1.8126 8.7893 10.6019 3.3600 13.6313 16.9913 12.5187 0.4327 -0.53% -0.46%   19 1.7891 8.7831 10.5722 3.1027 13.6669 16.7696 12.4314 0.4305 -1.23% -0.97%   20 1.7947 8.8175 10.6122 3.1433 13.6605 16.8238 12.4757 0.4321 -0.88% -0.60%   21 1.7341 8.8280 10.5621 3.4132 13.7066 17.1198 12.5294 0.4365 -0.45% 0.40%   22 1.8859 8.8222 10.7082 3.2509 13.6973 16.8901 12.5335 0.4307 -0.17% -0.18%   24 1.8805 8.9377 10.8183 3.3521 13.8169 17.1689 12.7235 0.4379 1.09% 0.73%   25 1.9108 8.8812 10.7920 3.4489 13.7622 16.8942 12.5760 0.4355	16	1.8603	8.8668	10.7271	3.1803	13.7514	16.9317	12.5885	0.4334	0.02%	-0.30%
18 1.8.126 8.7893 10.6019 3.3600 13.6313 16.9913 12.5187 0.4327 -0.53% -0.46%   19 1.7891 8.7831 10.5722 3.1027 13.6669 16.7696 12.4314 0.4305 -1.23% -0.97%   20 1.7947 8.8175 10.6122 3.1433 13.6805 16.8238 12.4757 0.4321 -0.88% -0.60%   21 1.7341 8.8200 10.5621 3.4132 13.7066 17.1198 12.5294 0.4365 -0.45% 0.40%   22 1.8859 8.8222 10.7082 3.2509 13.6888 16.9397 12.5776 0.4307 -0.07% -0.91%   23 1.8156 8.8508 10.6663 3.1929 13.6973 16.8901 12.5335 0.4339 -0.42% -0.18%   24 1.8805 8.9377 10.8183 3.3521 13.8169 17.1689 12.7235 0.4379 1.09% 0.73%   25 1.9108 8.812 10.7254 3.1320 13.7622 16.8942 12.5760 0.4355	17	1.9075	8.8511	10.7585	3.2098	13.7327	16.9425	12.6137	0.4360	0.22%	0.30%
191.78918.783110.57223.102713.666916.769612.43140.4305-1.23%-0.97%201.79478.817510.61223.143313.680516.823812.47570.4321-0.88%-0.60%211.73418.828010.56213.413213.706617.119812.52940.4365-0.45%0.40%221.88598.822210.70823.250913.688816.939712.57760.4307-0.07%-0.91%231.81568.850810.66633.192913.697316.890112.53350.4339-0.42%-0.18%241.88058.937710.81833.352113.816917.168912.72350.43791.09%0.73%251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.65140.43610.52%0.32%302.16968.980711.15023.707613.888117.595713.08390.4	18	1.8126	8.7893	10.6019	3.3600	13.6313	16.9913	12.5187	0.4327	-0.53%	-0.46%
201.79478.817510.61223.143313.680516.823812.47570.4321-0.88%-0.60%211.73418.828010.56213.413213.706617.119812.52940.4365-0.45%0.40%221.88598.822210.70823.250913.688816.939712.57760.4307-0.07%-0.91%231.81568.850810.66633.192913.697316.890112.53350.4339-0.42%-0.18%241.88058.937710.81833.352113.816917.168912.72350.43791.09%0.73%251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.4336302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.4	19	1.7891	8.7831	10.5722	3.1027	13.6669	16.7696	12.4314	0.4305	-1.23%	-0.97%
211.73418.828010.56213.413213.706617.119812.52940.4365-0.45%0.40%221.88598.822210.70823.250913.688816.939712.57760.4307-0.07%-0.91%231.81568.850810.66633.192913.697316.890112.53350.4339-0.42%-0.18%241.88058.937710.81833.352113.816917.168912.72350.43791.09%0.73%251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.4335	20	1.7947	8.8175	10.6122	3.1433	13.6805	16.8238	12.4757	0.4321	-0.88%	-0.60%
221.88598.822210.70823.250913.688816.939712.57760.4307-0.07%-0.91%231.81568.850810.66633.192913.697316.890112.53350.4339-0.42%-0.18%241.88058.937710.81833.352113.816917.168912.72350.43791.09%0.73%251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.4335302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43350.13%-0.27%331.87108.879510.75053.163413.760016.923412.60240.433	21	1.7341	8.8280	10.5621	3.4132	13.7066	17.1198	12.5294	0.4365	-0.45%	0.40%
231.81568.850810.66633.192913.697316.890112.53350.4339-0.42%-0.18%241.88058.937710.81833.352113.816917.168912.72350.43791.09%0.73%251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.41690.4307-1.34%-0.91%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43350.13%-0.27%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340<	22	1.8859	8.8222	10.7082	3.2509	13.6888	16.9397	12.5776	0.4307	-0.07%	-0.91%
241.88058.937710.81833.352113.816917.168912.72350.43791.09%0.73%251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.73616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43350.13%-0.27%331.87108.879510.57433.222013.648816.870812.46330.4340-0.97%-0.17%341.78278.791710.57433.222013.648816.870812.46330.43410.87%-0.14%351.89878.869910.76873.413513.779317.192812.69590.4341 </td <th>23</th> <td>1.8156</td> <td>8.8508</td> <td>10.6663</td> <td>3.1929</td> <td>13.6973</td> <td>16.8901</td> <td>12.5335</td> <td>0.4339</td> <td>-0.42%</td> <td>-0.18%</td>	23	1.8156	8.8508	10.6663	3.1929	13.6973	16.8901	12.5335	0.4339	-0.42%	-0.18%
251.91088.881210.79203.448913.766517.215412.71900.43351.06%-0.28%261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.4335302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43790.91%0.73%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	24	1.8805	8.9377	10.8183	3.3521	13.8169	17.1689	12.7235	0.4379	1.09%	0.73%
261.85478.870610.72543.132013.762216.894212.57600.4355-0.08%0.18%271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43350.13%-0.27%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	25	1.9108	8.8812	10.7920	3.4489	13.7665	17.2154	12.7190	0.4335	1.06%	-0.28%
271.82078.867510.68823.223313.733616.956912.56880.4313-0.14%-0.79%281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43790.91%0.73%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	26	1.8547	8.8706	10.7254	3.1320	13.7622	16.8942	12.5760	0.4355	-0.08%	0.18%
281.75038.822510.57283.065913.653616.719612.41690.4307-1.34%-0.91%291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43790.91%0.73%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	27	1.8207	8.8675	10.6882	3.2233	13.7336	16.9569	12.5688	0.4313	-0.14%	-0.79%
291.60888.839710.44853.411713.740317.152012.45960.4366-1.00%0.43%302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43790.91%0.73%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	28	1.7503	8.8225	10.5728	3.0659	13.6536	16.7196	12.4169	0.4307	-1.34%	-0.91%
302.16968.980711.15023.707613.888117.595713.08390.44073.96%1.37%311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43790.91%0.73%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	29	1.6088	8.8397	10.4485	3.4117	13.7403	17.1520	12.4596	0.4366	-1.00%	0.43%
311.90298.881910.78493.230613.776117.006712.65140.43610.52%0.32%321.95928.855010.81423.368813.731417.100112.70000.43790.91%0.73%331.87108.879510.75053.163413.760016.923412.60240.43350.13%-0.27%341.78278.791710.57433.222013.648816.870812.46330.4340-0.97%-0.17%351.89878.869910.76873.413513.779317.192812.69590.43410.87%-0.14%	30	2.1696	8.9807	11.1502	3.7076	13.8881	17.5957	13.0839	0.4407	3.96%	1.37%
32   1.9592   8.8550   10.8142   3.3688   13.7314   17.1001   12.7000   0.4379   0.91%   0.73%     33   1.8710   8.8795   10.7505   3.1634   13.7600   16.9234   12.6024   0.4335   0.13%   -0.27%     34   1.7827   8.7917   10.5743   3.2220   13.6488   16.8708   12.4633   0.4340   -0.97%   -0.17%     35   1.8987   8.8699   10.7687   3.4135   13.7793   17.1928   12.6959   0.4341   0.87%   -0.14%	31	1.9029	8.8819	10.7849	3.2306	13.7761	17.0067	12.6514	0.4361	0.52%	0.32%
33 1.8710 8.8795 10.7505 3.1634 13.7600 16.9234 12.6024 0.4335 0.13% -0.27%   34 1.7827 8.7917 10.5743 3.2220 13.6488 16.8708 12.4633 0.4340 -0.97% -0.17%   35 1.8987 8.8699 10.7687 3.4135 13.7793 17.1928 12.6959 0.4341 0.87% -0.14%	32	1.9592	8.8550	10.8142	3.3688	13.7314	17.1001	12.7000	0.4379	0.91%	0.73%
34   1.7827   8.7917   10.5743   3.2220   13.6488   16.8708   12.4633   0.4340   -0.97%   -0.17%     35   1.8987   8.8699   10.7687   3.4135   13.7793   17.1928   12.6959   0.4341   0.87%   -0.14%	33	1.8710	8.8795	10.7505	3.1634	13.7600	16.9234	12.6024	0.4335	0.13%	-0.27%
35   1.8987   8.8699   10.7687   3.4135   13.7793   17.1928   12.6959   0.4341   0.87%   -0.14%	34	1.7827	8.7917	10.5743	3.2220	13.6488	16.8708	12.4633	0.4340	-0.97%	-0.17%
	35	1.8987	8.8699	10.7687	3.4135	13.7793	17.1928	12.6959	0.4341	0.87%	-0.14%

两种优化算法收敛结果如图 5,6 所示。从图中可以看出,两种算法达到收敛的迭代次数相当,目标函数的收敛值一致。



所得的优化解相同,通过得到的设计变量值反馈到 FFD 船型变换,获得最优船型如图 7,8,可以看出 首部和方案一得到的优化船型基本一致,尾部线型也明显发生变化,排水量降幅为 0.36%,符合要求。



图 7 母型船和优化船型横剖线对比图



图 8 母型船和优化船型整体和局部纵剖线对比图

为了验证阻力优化情况,同样将所得优化船型采用 naoe-FOAM-SJTU 求解器进行数值计算。得到阻力 值与母型船阻力情况进行对比。为了更加详细地了解球首部的变形对阻力的影响情况,从数值模拟中可以 得到自由面兴波情况和首部压力分布情况进行对比分析。

表 7	母型船和优化船型阻力详细对比

	Fr=0.1834				Fr=0.2342		日标函数AI	北北島
	压阻力	摩擦阻力	总阻力	压阻力	摩擦阻力	总阻力	日小山致/1N	小小里 /m3
	/N	/N	R <sub>t1</sub> /N	/N	/N	R <sub>t2</sub> /N	$\mathbf{K}_{t1}$ 0.7+ $\mathbf{K}_{t2}$ 0.5	
母型船	1.8191	8.8888	10.7079	3.3308	13.7682	17.099	12.6253	0.4347
优化船型	1.6850	8.8088	10.4938	3.1844	13.7029	16.8873	12.4119	0.4331
降幅	-7.37%	-0.90%	-2.00%	-4.39%	-0.47%	-1.24%	-1.69%	-0.36%



图 9 母型船和优化船型自由面波形图对比(Fr=0.1834)



图 10 母型船和优化船型自由面波形图对比(Fr=0.2342)



图 11 母型船和优化船型首部压力云图对比(Fr=0.1834(左), Fr=0.2342(右))

从表 7 中可以看出优化船型在两个速度下压阻力均得到降低,分别降低 7.37%和 4.39%;从自由面兴 波图(图 9,10)可以明显看出在 Fr=0.1834 情况下,优化船型首部兴波明显降低,而在 Fr=0.2342 情况下,优化船型首部兴波较母型船变化不是很明显。而从压力云图(图 11)对比分析可以明显看出:在两个航速 下航行,优化船型首部所受压力较母型船都有显著降低。而就摩擦阻力而言,也有所降低,分别为 0.90%和 0.47%,这主要因为优化船型较母型船的湿表面积有所降低。优化目标函数:两个航速下的总阻力综合情况得到 1.69%的降幅。

## 4 结论

- (1) 本文详细介绍了课题组船型优化求解器 OPTShip-SJTU 用于船型优化实例的数值方法与流程。
- (2) 本文基于 OPTShip-SJTU 成功针对某实用船船型进行了优化设计,使得两个航速下的总阻力线 性组合最优,得到优化船型。
- (3) 根据课题要求的约束条件:排水体积变化控制在±0.4%,为了获得较大的设计空间,同时对首 部和后半体进行变形。结果表明总阻力降低。
- (4) 本文同时采用两种全局优化算法——遗传算法和粒子群优化算法进行优化计算,确保优化收 敛解的可靠性。两种算法达到收敛的迭代次数相当,但粒子群算法评价目标函数次数较少。最

- 终目标函数的收敛值一致,确保优化过程可靠,优化结果可信。
- (5) 本文通过优化船型和初始船型的线型、阻力值对比,以及自由面波形、首部压力分布等细节的 对比分析,证明了最优船型的阻力降低是合理有效的。
- (6) 接下来可以针对两个航速下的总阻力值进行多目标优化设计,寻求综合阻力性能更优的船型。

## 5 致谢

本文工作得到国家自然科学基金项目(51379125, 51490675, 11432009, 51579145)、长江学者奖励计划 (T2014099), 上海高校东方学者特聘教授岗位跟踪计划(2013022), 上海市优秀学术带头人计划 (17XD1402300),上海市船舶工程重点实验室基金项目(K2015-11),以及工信部数值水池创新专项 VIV/VIM 项目(2016-23/09)的资助。在此一并表示衷心感谢。

#### 参考文献

- [1] Leotardi C, Campana E F, Diez M. Resistance reduction of a military ship by variable-accuracy metamodel-based multidisciplinary robust design optimization[C] Vi International Conference on Computational Methods for Coupled Problems in Science and Engineering, Coupled Problems. 2015..
- [2] Diez M, Serani A, Campana E F, et al. Multi-objective Hydrodynamic Optimization of the DTMB 5415 for Resistance and Seakeeping[C] FAST 2015 -, International Conference on FAST Sea Transportation. 2015.
- [3] Huang F, Wang L, Yang C, et al. Hull form optimization of a TriSWACH for reduced drag[C] FAST. 2015.
- [4] 詹成胜,刘祖源,冯佰威,等. 基于 CFD 的船舶球首型线自动优化[J]. 船舶力学, 2012, 16(4):350-358.
- [5] Wu J, Liu X, Zhao M, et al, Neumann-Michell theory-based multi-objective optimization of hull form for a naval surface combatant[J], Applied Ocean Research, 2017, **63**: 129-141.
- [6] 刘晓义,吴建威,万德成,基于遗传算法与 NM 理论的船型优化,水动力学研究与进展,2016,31(5):535-541.
- [7] Liu X, Wu J, Wan D. Multi-Objective Optimization for a Surface Combatant Using Neumann-Michell Theory and Approximation Model[C] Proceedings of the 12th International Conference on Hydrodynamics(ICHD2016). September. 18-23, 2016, Egmond aan Zee, The Netherlands.
- [8] 沈志荣,叶海轩,万德成.船舶在迎浪中运动响应和波浪增阻的 RANS 数值模拟[J].水动力学研究与进展: A 辑. 2012, 27(6): 621-633.
- [9] Ye H., Shen Z., Wan D. Numerical prediction of added resistance and vertical ship motions in regular head waves[J]. Journal of Marine Science and Application. 2012, 11(4): 410–416.