THE QUASI-3D INVERSE DESIGN MODE

INTRODUCTION

MULTALL-OPEN-20.6 has been developed to work in the inverse mode in which a blade surface pressure distribution is input and a blade producing that distribution is designed. At present this is limited to quasi-3D (Q3D) calculations on a blade-to-blade stream surface but it is hoped to extend it to a fully 3D design mode in future. The calculation remains fully viscous and the stream surface thickness and radius can change through the blade row. Both suction and pressure surfaces of the blade can be specified but this does not allow any control on the blade thickness, which may become negative. To overcome this an option to relax the thickness to a specified value is included, when this is used the pressure surface pressure distribution will differ slightly from that specified but the suction surface pressures should still be correct.

The method works especially well at high Mach numbers and is particularly good a cancelling shock wave interactions with the blade surfaces. However, it is difficult to avoid generating shocks at the leading or trailing edges of high Mach number blades. Run times are of order 2 minutes for an initial design but several iterations may be needed.

METHOD

Several algorithms for moving the blade surfaces have been tried but the only one which seems generally useable is when the condition of no flow through the blade surface is replaced by a condition in which the local flow through the blade surfaces is proportional to the difference between the specified pressure the currently calculated pressure. The mass flux through the blade surfaces is updated in this way on every time step. If flow is entering the blade from the main stream then its properties are taken as those on the blade surface, if flow is entering the mainstream through the blade surface then its properties are taken to be those at one grid point away from the surface. This simple expedient is stable and has negligible effect on the accuracy since the surface flows should become zero on convergence. After doing this for about 500 time steps new surface streamlines are calculated and the blade geometry is updated to follow them. This process is repeated until the changes in geometry become negligible, usually after a maximum of 40 updates, in most cases the geometry will become fixed after far fewer updates.

The calculation is best started from a standard MULTALL data set for an initial approximate design of the blade, which can be obtained from STAGEN. This initial design sets the blade pitch:chord ratio (i.e. number of blades) and the inlet and exit boundary conditions. This data set is run to near convergence, typically 2500 steps, before the inverse mode is started. After that the calculation is continued and on every time step the surface mass flows are calculated as described above. The surface mass flows are summed to find the net flow through the surface and on the suction surface the average flow is then subtracted from the local flows so that the net flow becomes zero. On the pressure surface the surface mass flows are summed as above but when the average flow is subtracted from the local flows it is adjusted so as to provide a specified trailing edge thickness. This is continued on every time step for typically 500 steps, without changing the blade geometry.

Around every 500 time steps the blade geometry is updated. Starting from the leading edge point, which remains fixed, the surface flows are summed to trace a new surface streamline. If the net surface mass flux is zero then the trailing edge point will also remain fixed but if a trailing edge thickness is specified the net flux on the pressure surface will be adjusted to provide that thickness. The blade geometry is then relaxed towards the new calculated surface streamlines, the relaxation factors are input as data but are typically 2.0. However, fixing the leading and trailing edge points is too great a constraint on the blade geometry and so the required exit flow angle must also be specified and at every geometry update the blade is rotated (strictly sheared) to try to achieve that angle.

Since the blade loading (i.e. angular momentum change), the pitch:chord ratio and the exit Mach number have been specified there is only one compatible exit flow angle. If the specified flow angle does not agree with this then the specified blade loading cannot be achieved. Nevertheless the calculation should converge and will usually obtain blade surface pressure distributions which are very similar in shape to those specified but which differ in pressure level, so as to match the imposed exit angle. The blade obtained will usually be a good design for the specified exit flow angle. However, the compatible exit flow angle and the compatible pitch:chord ratio (number of blades) are calculated (this is surprisingly difficult) and are printed out at the end of the calculation. For a specified blade spacing (pitch/chord ratio) and a specified exit Mach number there is a maximum possible angular momentum change of the flow, which usually occurs when the exit angle is about +/-45deg. If the specified load exceeds this maximum load then the iteration to calculate the compatible exit angle will not converge and the value printed out will probably be close to zero or to 90deg. The iteration may also be unstable when the exit angle is close to +/-45 deg as there are then two possible angles for the same loading, one greater than 45deg and one less. If the iteration does converge, and the compatible exit flow angle printed out is realistic, then the calculation may be repeated with either the number of blades changed to the compatible number, in which case it should produce a design with the specified surface pressures and the specified exit angle, or with the specified exit angle changed to the compatible angle, in which case it should produce a design with the specified blade numbers and the specified surface pressures. An alternative option is to iteratively adjust the specified exit flow angle to the calculated compatible angle during the calculation. This works satisfactorily for low exit angles, say < 65deg or > -65deg, but may become unstable for higher angles and it clearly will not work if the iteration to find the compatible angle does not converge, and so should be used with caution.

Specifying both blade surfaces in this way allows no control on the blade thickness which may become unacceptably thin or even negative. To try to avoid this a minimum acceptable thickness, equal to some fraction of the initial blade thickness may be specified. Also a specified thickness can be set, this is a multiple of the initial blade thickness plus specified leading and trailing edge additions. On every geometry update the new blade thickness can be relaxed towards this specified thickness. If the input relaxation factor is zero then the thickness obtained is that calculated from the specified pressure distribution alone, if the relaxation factor is 1.0 the thickness will be close to the specified thickness. In the latter case the surface pressure distribution will differ from that specified and continuity will not be satisfied because the flow through the blade surfaces will not become zero. In many cases a low relaxation factor, say 0.1, can be used and the pressure distribution obtained will then be very similar to that specified and the thickness will be realistic. Specifying the blade thickness only affects the flow on the pressure surface and the suction surface geometry is always obtained from the specified pressure distribution.

The calculation is first run for NINV_START time steps without any geometry change to build up a near converged solution for the initial design. The blade geometry is then updated every NINV_UP steps until a total of NINV_END steps have been performed. About 40 geometry updates are usually sufficient to obtain the final blade shape, although in many cases far less than this are needed, so if NINV_START is 2500 and NINV_UP is 500 then NINV_END would be about 22,500, 25,000 is often used. It is usually desirable to continue the calculation a little further, without changing the geometry, to ensure that the final solution if fully converged on the new geometry, so NSTEPS, as set in the main MULTALL data set, should be about 2000 steps greater than NINV_END.

RUNNING THE INVERSE MODE

The program starts by reading in a standard MULTALL data set, the only addition to that is to input a new variable, IF_INV, along with the existing IF_RESTART in card 9. If IF_INV is not present or is zero than a conventional MULTALL calculation is performed. If IF_INV = 1 then the inverse design mode will be used. One other change to a standard MULTALL data set may be needed, it has been found that the datum stream surface thickness, which was fixed at 5% of the blade chord, may be too thick when stream surfaces are curved causing the blade geometry to vary between the two surfaces. To prevent this an option to read in the datum stream surface thickness is added to Card Q3D1 which now reads in Q3DFORCE and TKSS_REF, the latter should be set to a lower value, typically 0.02 , although the original datum of 0.05 is OK in most cases. Too low a value of TKSS_REF may cause instability.

If the inverse mode is specified then data is also read in from a new input file called "inverse.in" the details of which are described below. This contains the values of NINV_START, NINV_END and NINV_UPP , the specified blade surface pressure distribution and various control parameters as described in the next section.

Although the calculation may be started with an arbitrary guess of the required surface pressure distributions this is unlikely to produce a blade loading compatible with the required exit flow angle and boundary conditions. Hence it is best to start from the pressure distribution of an initial design and iteratively improve it. The initial blade geometry, which may be generated by STAGEN, should be as close as possible to the required final design. In particular the initial geometry sets the number of blades (pitch:chord ratio), the inlet and exit flow conditions and the stream tube thickness and radius. Its surface pressure distribution should be as close as possible to that required for the final design, in fact the method works best when it is used to make minor changes to an existing blade.

To do this set IF_INV =1 and NSTEPS = 5010 in the main MULTALL data set. Also set the convergence limit, CONLIM, to a very small number, say 0.000001, to prevent premature convergence. Set NINV_START = 5000 in the "inverse.in" data set. The specified pressures in "inverse.in" will not be used at this stage and so can be arbitrary.

Run the calculation and after 5000 (NINV_START) steps it will write the current solution to a new file called "initial_inverse.in", this contains a smoothed copy of the blade surface pressures calculated for the initial design. The calculation will stop after NSTEPS (5010) steps. No inverse calculations have been performed at this stage.

Copy "initial_inverse.in" to "inverse.in". Inspect the surface pressure distributions and adjust them to change any undesirable features whilst trying to maintain the average pressure roughly constant on each blade surface. Change NINV_START to 2500 and NINV_END to 25000 in "inverse.in". Now reset NSTEPS to NINV_END + 2000 in the main data set, start the calculation with this new version of "inverse.in" and run to completion after NSTEPS steps.

Inspect the calculated blade pressure distributions and decide if further changes are necessary, if so copy the output file "final_inverse.in" to "inverse.in", change the specified pressures and run again. Note that the pressure distributions in "final-inverse.in" should be compatible with the specified exit flow angle and so may be different from those in "initial_inverse.in" which are not necessarily compatible with the specified exit angle.

If the blade thickness is not acceptable then either the specified pressure distributions can be changed or the blade geometry may be relaxed towards a specified thickness distribution. In some cases the blade thickness obtained is extremely sensitive to the specified pressures around the leading edge and these should be adjusted very gradually, similarly the trailing edge thickness can be extremely sensitive to the local pressures.

It is found that increasing the specified pressures near the leading edge and reducing them near the trailing edge generally thickens the blade, and vice-versa to thin it. This may be thought of as adding sources near the leading edge and sinks near the trailing edge. To help with this an option to add linear variations of specified pressure is included. Pressures PADD_I1 and PADD_IM are input in 'inverse.in" and a linear variation of pressure with meridional distance from +PADD_I1 at the leading edge to –PADD_I1 at the trailing edge is added to the specified pressures on the I=1 blade surface, similarly for PADD_IM. This linear variation in pressure does not affect the total blade loading. To thicken the blade usually set PADD_I1 = PADD_IM with both of them positive, typical values depend on the Mach number levels but for near sonic conditions PADD_I1 = PADD_IM = 3000 N/m^2 is typical. Making PADD_I1 and PADD_IM the same changes the loading distribution but not the overall load on the blade.

The specified thickness distribution is obtained by first scaling the initial thickness by FTK_SCALE then adding an additional thickness (TK_ADD_LE x meridional chord) near the leading edge and (TK_ADD_TE x meridional chord) at the trailing edge. Both TK_ADD_LE and TK_ADD_TE can be negative if it is required to locally thin the blade. On every geometry update the thickness is relaxed towards this specified thickness by a factor RF_THICK, this is in addition to the thickness changes made from the main algorithm. A low value, say RF_THICK = 0.1, will often provide a realistic thickness without seriously compromising the pressure distribution. A high value, RF_THICK = 1.0, will give close to the specified thickness distribution but the pressure distribution on the pressure surface will be significantly compromised and continuity will not be satisfied. It is sometimes found that increasing the leading edge thickness also increases the trailing edge thickness and it is hard to overcome this.

The trailing edge thickness is set by the scaled initial thickness plus TK_ADD_TE even when RF_THICK is zero. This is achieved by adjusting the pressure surface mass flux and does not cause a continuity error.

There is no clear convergence criterion, the changes in flow on each geometry update should reduce gradually but will seldom become zero. Generally convergence may be assumed when EAVG becomes less than 0.0005 and ECONT is less than 0.01. If the EAVG values do not reduce after many geometry updates then the relaxation factors RFAK_I1 and RFAK_IM should be reduced and the rotation factor, ROT_FAK, may also need to be reduced. ECONT may not become low (< 0.01) if the blade thickness is being forced via RF_THICK.

On completion the program writes out the conventional MULTALL output files plus a file named "newgrid" , this contains the new blade upper (I=1) surface coordinates and new blade thickness. They may be cut and pasted into the original MULTALL data set to obtain a data set for the redesigned blade. The blade axial and radial coordinates are not changed from those in the initial data set.

A warning on plotting the resulting geometry, if using the original plotting program PLOTALL-17.1. In previous versions of MULTALL the blade geometry is only passed to the plotting file once at the start of the calculation (because in a conventional calculation it does not change) and previous versions of the plotting program PLOTALL only read the geometry file once. The latest version MULTALL-OPEN-20.6 writes the geometry file every time that an output is requested, using NOUT. If the old plotting program PLOTALL-17.1 is used for output from the inverse mode then only the geometry of the first plotter file to be output will be used and plotted, this will be different from any later outputs of the modified design. Hence the option to use NOUT to output multiple plot files during the iterations should not be used. Only the final solution should be plotted. A modified version of the plotting program, PLOTALL-20.1, is attached and should be used with output from version 20.6, this will read in and plot the correct geometry for each output requested so NOUT can be used.

DATA INPUT FOR THE FILE “inverse.in”

All data is in Free Format.

CARD 1 IFINV_I1, IFINV_IM

IFINV_I1	Design the I = 1 surface if this = 1, do not design it if it = 0.
IFINV_IM	Design the I = IM surface if this = 1, do not design it if it = 0.

IF IFINV_I1 = 1 then input the following data, Cards 2 and 3

CARD 2 NIN — The number of points at which the I = 1 surface pressure will be input, typically about 20 points.

CARD 3 For N = 1 to NIN read X_IN(N), P_IN(N)

X_IN(N)	The fraction of meridional chord at which the pressure is being input.
P_IN(N)	The specified blade surface pressure on the I = 1 surface at these points. In N/m2 .

IF IFINV_IM = 1 then input the following data, Cards 4 and 5

CARD 4 NIN — The number of points at which I = IM surface pressure will be input, typically about 20 points.

CARD 5 For N = 1 to NIN read X_IN(N), P_IN(N)

X_IN(N)	The fraction of meridional chord at which the pressure is being input.
P_IN(N)	The specified blade surface pressure on the I = IM surface at these points. In N/m2 .

CARD 6 A2_SPEC_DEG — The specified exit flow angle in degrees. This is positive if the associated flow vector has a positive component in the direction of rotation.

CARD 7	ROT_FAK	A relaxation factor on the change in exit flow angle between iterations. Usually it is OK to set this =1.0 but reduce it to 0.5 if any instability in the exit angle or mass flow rate.
CARD 8	ANG_FAK	The specified exit angle is relaxed towards a calculated compatible angle by this factor on every iteration. If this option is to be used set ANG_FAK = 0.1, set it = 0.0 to keep the original specified angle A2_SPEC_DEG. The process is sometimes unstable especially at high absolute values of angle, say greater than 65 deg so use it with caution.
CARD 9	RFAK_I1, RFAK_IM	Relaxation factors on the changes in blade geometry on the I =1 and I=IM blade surfaces. Usually set both = 2.0 but reduce to 1.0 or even 0.5 if the geometry changes are not converging.
CARD 10	N_SMTH, F_SMTH	The blade surface movements are smoothed by N_SMTH passes of a smoothing with smoothing factor F_SMTH. This helps stability. Typically set N_SMTH = 5, F_SMTH = 0.5. Increasing N_SMTH improves stability without significantly compromising the final solution.
CARD 11	NINV_START, NINV_END, NINV_UPP	The inverse mode starts after NINV_START steps, typically 2500. The geometry changes end at NINV_END steps, typically 25000 . The blade geometry is updated every NINV_UPP steps, typically 500 but it may be desirable to increase it for cases with a large number of grid points which are slow to converge.

CARD 12 FTK_SCALE, FTK_MIN, TK_ADD_LE, TK_ADD_TE, RF_THICK, JSET_TK

FTK_SCALE The initial blade thickness is scaled by FTK_SCALE before being used to set the specified thickness.

FTK_MIN The original thickness is scaled by FTK_MIN to set the minimum acceptable thickness.

TK_ADD_LE An addition thickness TK_ADD_LE x (meridional chord) is added at a grid point JSET_TK points behind the leading edge. This is added to the scaled thickness of the original blade to obtain the specified thickness.

TK_ADD_TE An additional thickness TK_ADD_TE x (meridional chord) is added at the trailing edge. This is added to the scaled thickness of the original blade to obtain the specified thickness.

RF_THICK The thickness is relaxed towards the specified thickness by RF_THICK. Set = 0 to use the thickness obtained from the specified pressure distribution on the pressure surface. Set = 1.0 to use the specified thickness. Typically set 0.1 to obtain a suitable compromise.

JSET_TK The leading edge thickness, TK_ADD_LE, is applied at JSET_TK grid points downstream of the leading edge. Upstream of this point an elliptic thickness distribution is applied. Typically JSET_TK = 5 .

Note All the thickness referred to above are the tangential thickness.

CARD 13 PADD_I1, PADD_IM

PADD_I1 The specified pressure on the I=1 blade surface is increased by PADD_I1 at the leading edge and decreased by PADD_I1 at the trailing edge with a linear variation with meridional chord between those points. In N/m^2 .

PADD_IM The specified pressure on the I=IM blade surface is increased by PADD_IM at the leading edge and decreased by PADD_IM at the trailing edge with a linear variation with meridional chord between those points. In N/m^2 .

Note Making both PADD_I1 and PADD_IM positive tends to thicken the blade and making them both negative tends to thin it. Typical values depend on the Mach number level but for near sonic conditions values of a few thousand N/m^2 are typical.

TEST CASES SUPPLIED.

The initial design MULTALL file and the final "inverse.in" file are supplied for the following test cases.

aerofoil.dat	A simple aerofoil with a shock which is cancelled before it hits the suction surface.
impulse-turbine .dat	An impulse turbine rotor with the suction surface just above Mach 1 but no shocks.
hp-turb-stator.dat	A typical high pressure gas turbine stator with exit Mach number about 1.0 and continuous acceleration on the blade surfaces.
lp-aero-turbine.dat	A typical low pressure aero engine blade, very thin, with Mach number just subsonic.
compr-hub.dat	A typical compressor hub section, high subsonic.
supercrit.dat	A compressor rotor with peak Mach number around 1.2 but no shocks on the suction surface.
trans-fan.dat	A transonic compressor blade with inlet Mach number around 1.3 but with the bow shock cancelled before it meets the suction surface.

low-reacn.dat	A low reaction turbine rotor blade.
highmach-nozzle.dat	A typical last stage LP steam turbine stator with exit Mach number 1.8.
lp-st-tip-20k.dat	A last stage LP steam turbine rotor tip section with exit Mach number around 1.8.
lp-st-mid.dat	A last stage LP steam turbine rotor mid section with radius change and stream tube divergence , exit Mach number around 1.5
lp-st-hub.dat	A last stage LP steam turbine hub section, near impulse with stream tube divergence and shock cancellation.
rad-casc+rotn.dat	A rotating radial flow cascade with geometry typical of a centrifugal compressor.
mixed-fan.dat	A mixed flow, low speed, fan impeller with radius change and stream tube contraction.
ogv.dat	An outlet guide vane from a LP aero engine turbine.