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ANALYTICAL INVESTIGATION IN BENDING CHARACTERISTIC OF TWISTED STACKED-TAPE CABLE CONDUCTOR

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SUMMARY

An analytical model to evaluate bending strains of a **Twisted Stack-Tape Cable (TSTC)** conductor has been developed.

Two models, **No-Slip Model (NSM)** and **Perfect-Slip Model (PSM)**, are presented, and critical current degradation due to bending is discussed.

Through a comparison with experimental results obtained for a soldered 32-tape YBCO TSTC conductor, it was found that a **Perfect-Slip Model (PSM)** taking into account the slipping between tapes in a stacked-tape cable during bending gives much better estimation of the bending performance compared to a **No-Slip Model (NSM)**.

In the **PSM** case the tapes can slip so that the internal longitudinal axial **strain can be released**. The longitudinal strains of compression and tension regions along the tape are balanced in one twist-pitch and **cancel out evenly in a long cable**. Therefore, in a cable the strains due to bending can be minimized. This is an important **advantage of a TSTC conductor**.

The effect of the **cable diameter size** on the bending strain is expected to be **minor**, and **all tapes** composing a TSTC conductor have the **same strain** response under bending, therefore the **cable critical current** can be characterized from a single tape behaviour.

ACKNOWLEDGMENT

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Analysis Modeling

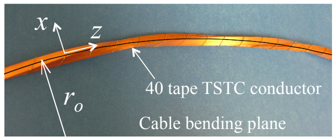
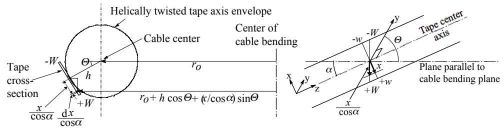


Illustration of a 40 tape Twisted Stacked-Tape Cable (TSTC) conductor bent with the bending radius r_o=500 mm.



Schematic illustrations showing a bending model of a TSTC conductor: (a) a cross-section of a tape in a TSTC conductor bent with the radius r_o. (b) an enlarged view of a part of a twisted tape.

Bending Strain

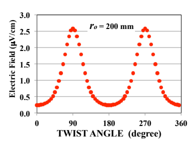
(a) **No-Slip Model (NSM)**: 2G tapes in a TSTC conductor are rigidly stacked and they do not slip between tapes.

$$\varepsilon_b \approx \frac{x\sin\theta + h\cos\theta\cos\alpha}{r_o} \qquad \alpha = \tan^{-1}(2\pi h/L_p) \qquad \theta = \frac{2\pi z}{L_p}$$

(b) **Perfect-Slip Model (PSM)**: Tapes can slip so that the internal axial strain can be released.

$$\varepsilon_b = \frac{x\sin\Theta}{r_o}$$

Critical Current



Electric-field distribution calculated from bending strain distribution along the tape of one twist pitch when the total voltage of one twist pitch reached the critical current criterion of E_c. Tape width $2w$=4 mm, twist-pitch L_p=200 mm, h=0, n=25, r_o=200 mm.

Total voltage of one twist-pitch at the tape current I_o is given by

$$V = \int_0^{L_p} \Delta V\, dz = \int_0^{L_p} E_c \left(\frac{I_o}{I_{c\Theta}}\right)^n dz = E_c\, {I_o}^n \int_0^{L_p} {I_{c\Theta}}^{-n}\, dz$$

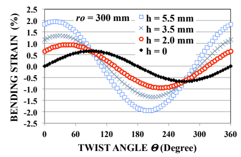
Tape critical current $I_{c\,Tape}$ for a twisted bent tape is given by

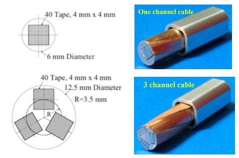
$$I_{c\,Tape} = \sqrt[n]{\frac{T_p}{\int_0^{T_p} {I_{c\Theta}}^{-n}\, dl}} = \sqrt[n]{\frac{2\pi}{\int_0^{2\pi} {I_{c\Theta}}^{-n}\, d\Theta}}$$

The tape critical current was evaluated with Θ=5 degree step analysis using Microsoft Excel®. In this case the equation is reduced to

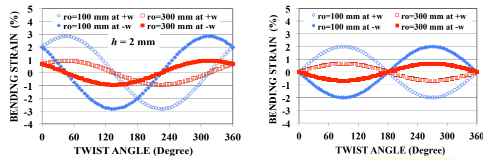
$$I_{c\,Tape} = \sqrt[n]{\frac{T_p}{\int_0^{T_p} {I_{c\Theta}}^{-n}\, dl}} = \sqrt[n]{\frac{72}{\sum {I_{c\Theta}}^{-n}}}$$

Strain Distribution Results



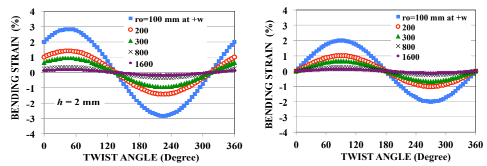


(a) The bending strain distribution for NSM along a twisted tape of 4 mm width and 200 mm twist-pitch bent with the radius of r_o=300 mm with various tape off-center distance h values up to 5.5 mm. (b) The insert figures show a single stack cable with $0 \le h \le 2$ mm and three-stack cable with $1.5 \le h \le 5.5$ mm.



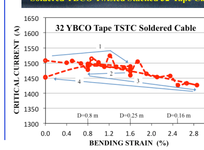
(a) No-Slip Model **(b) Perfect-Slip Model**

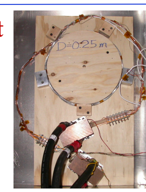
Bending strain distributions for a tape of 4 mm width and the twisted pitch 200 mm along a tape as a function of the twist angle Θ. The curves show the strains at the edges of $x = \pm w$ for the bending radius r_o=100 mm and 300 mm. (a) No-Slip Model (NSM) with h=2 mm, and (b) Perfect-Slip Model (PSM).

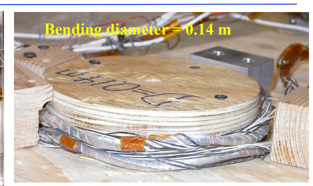


Bending strains at the tape edge x=+w for (a) No-Slip Model (NFM) with h= 2 mm and (b) Perfect-Slip Model (PSM) calculated for various bending radiuses r_o. The tape width $2w$ and twist-pitch L_p are 4 mm and 200 mm, respectively.

Bending Test Result

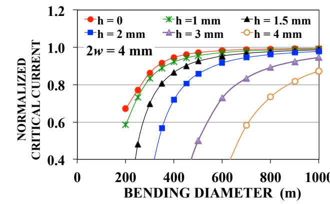




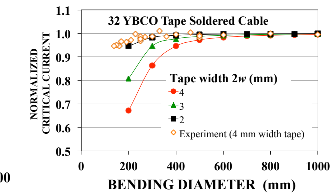


The critical currents at 77 K of a soldered 32-tape YBCO TSTC conductor as a function of the bending strain. The arrow lines with numbers indicate the test order.

Critical Current Results



Normalized critical current for various values of h as a function of the bending diameter. Tape width $2w$=4 mm, twist-pitch L_p=200 mm, and n=25.



Normalized critical current for PSM with various tape width $2w$ as a function of the bending diameter, comparing with an experimental result of 4 mm width, 32-tape soldered YBCO TSTC conductor. Twist-pitch L_p=200 mm, and n=25.

CONCLUSIONS

In the No-Slip Model (NSM) case, 2G tapes in a TSTC conductor are rigidly stacked and they do not slip between tapes. On the other hand in the Perfect-Slip Model (PSM) case, the tapes can slip so that the internal axial strain can be released.

The stacked tapes are twisted, therefore in each half cycle of the twisting the strains change from tension to compression. The internal longitudinal strains during bending can be released in a full twist-pitch even for a long cable. Therefore the strains due to a cable bending can be minimized. This is an important and beneficial consequence of the twisting of a TSTC conductor.

Strains over the width are induced during the bending of the cable. This strain causes the critical current degradation due to bending. The bending strain effect on the critical current of a TSTC conductor was evaluated for various bending diameters.

Based on the Perfect-Slip Model (PSM), the critical current of a twisted tape was calculated for one full twist-pitch length and compared with experimental results. The agreement was not great, however it was much better than what estimated with the No-Slip Model (NSM).

The calculated result for PSM showed more degradations than the experimental results. This could be due to the soft bending applied in the experiment to respect the natural irregularity during cable bending. Taking into account this observation the analytical results seem to show a fairly good agreement with the experimental results.

A narrower tape gives less degradation for bending. The twist-pitch effect on the bending strain is minor.

Further investigation to explain the discrepancy between experimental results and the model analysis will be necessary using both experiments of various TSTC conductors and Finite Element Analysis.